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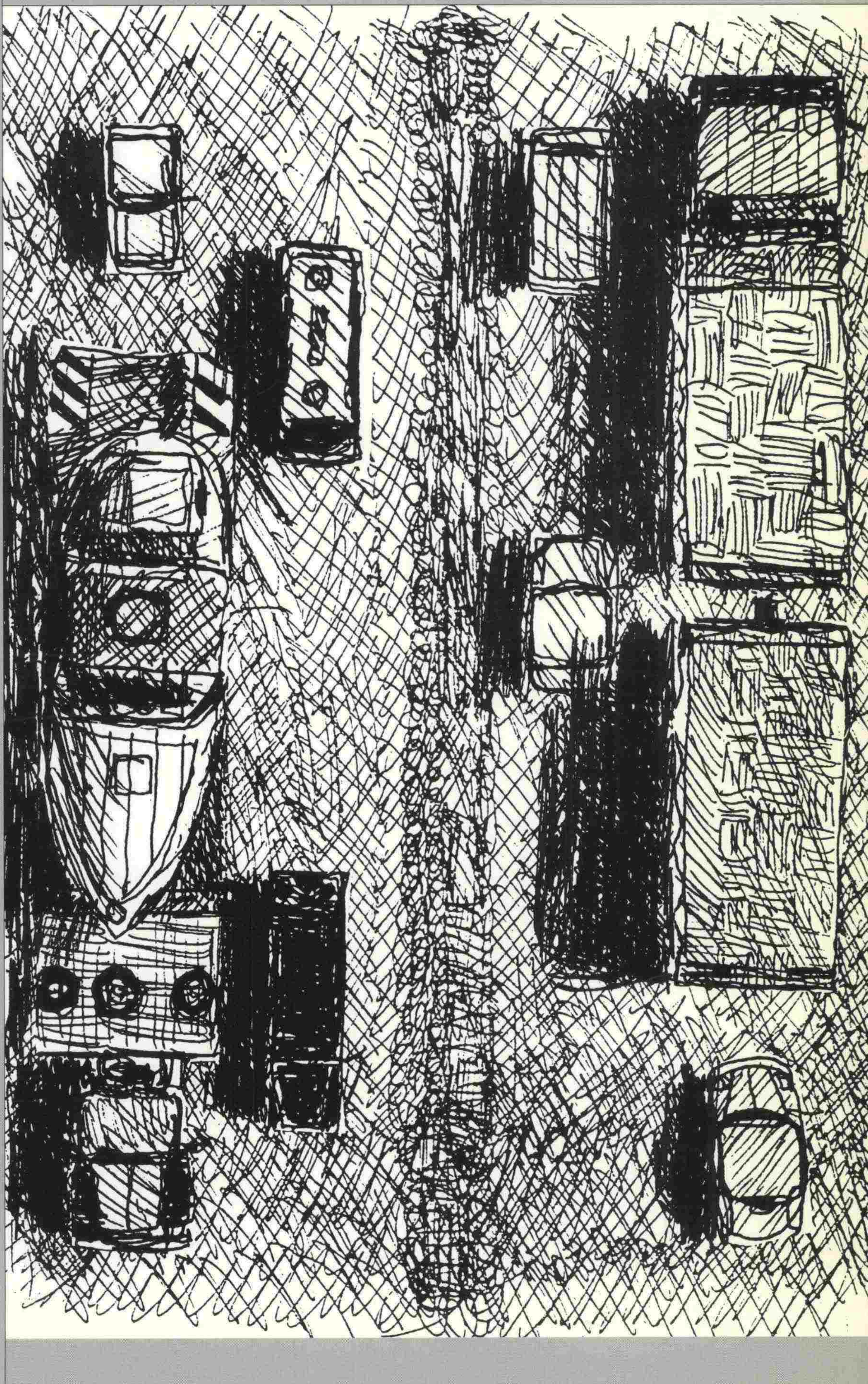

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Keywords: heavy vehicle, traffic flow, freeway, field study, simulation

ABSTRACT

The impact of heavy vehicles on traffic flow is different from that of light vehicles. Heavy vehicles are large in size and have operating capabilities that are inferior to those of light vehicles. Heavy vehicles need more time, space, and width when turning from the main stream to a ramp and from a ramp to the main stream. In Finland the speed limit for all heavy vehicles except buses is 80 km/h and in new vehicles the maximum speed is limited to about 90 km/h using electronic equipment.

This study is based on field measurements and literature review. The idea was to clarify the impact of heavy vehicles on freeway traffic flow and at the same time to procure parameters to extend the use of the microsimulation program HUTSIM from traffic signal simulation to freeway simulation. Field measurements were carried out with the license plate method using video cameras and with car following and moving observation methods using an instrumented vehicle. Data gathered from the automatic traffic measurement system (LAM) were also used.

The acceleration rate and deceleration rate fluctuated between 1.1 and -1.1 m/s^2 and the standard deviation of the acceleration rate (acceleration noise) was low when the test vehicle followed a heavy vehicle at a constant distance. The average gap between the test vehicle and a heavy vehicle in front was 1.9 seconds just before overtaking. The corresponding value to a heavy vehicle behind was 1.4 seconds just after overtaking. A heavy vehicle followed a light vehicle at a larger gap than a light vehicle followed a heavy vehicle.

The average running speed varied between 84 and 91 km/h when the instrumented vehicle followed a heavy vehicle at a constant distance on Hämeenlinnanväylä (speed limit 120 km/h). The average running speed at Ring Road III (speed limit 80 km/h) varied between 60 and 81 km/h towards east and between 62 and 80 km/h towards west.

The travel speed differences between light and heavy vehicles varied between 4 and 13 km/h on jug-handle ramps and were about 9 km/h on loop ramps. The differences in travel speed between light vehicles and heavy vehicles were usually higher on downgrades than on upgrades. The travel speed differences between light and heavy vehicles varied with hilliness (m/km) and speed limits. The space mean speeds of heavy vehicles were 3-5 km/h lower at LAM sites with 80 km/h speed limit, 9-14 km/h lower at sites with 100 km/h speed limit and 19-25 km/h lower at sites with 120 km/h speed limit compared to those of light vehicles. The overall speed decreased as proportion of heavy vehicles increased and a little faster at high speed limit areas than at low speed limit areas. The decrease in speed when flow increased seemed to be a little faster on the basic lane than on the passing lane.

The number of platooning vehicles increased as the flow rate increased. The overall proportion of heavy vehicles leading a platoon was higher than the proportion of heavy vehicles in the traffic stream. The mean platoon length increased when the flow rate and proportion of heavy vehicles increased. However, the effect of flow rate was dominating. On the basic lane the mean platoon length increased faster with flow than on the passing lane.

The PCE (Passenger Car Equivalent) value calculated for heavy vehicles ranged from 1.7 to 7.2 on ramps, from 6.9 to 22.1 on upgrades, and from 3.2 to 4.7 on downgrades. The estimated PCE values were lower at 120 km/h speed limits than at 80 and 100 km/h. The PCE values varied for different level-of-services (LOS) and also for different lanes.

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Asiasanat: raskaat ajoneuvot, liikennevirta, moottoritiet, kenttätutkimus, simulointi

Aiheluokka: 21, 25

TIIVISTELMÄ

Raskaiden ajoneuvojen vaikutus liikennevirtaan poikkeaa kevyiden ajoneuvojen vaikutuksesta. Raskaat ajoneuvot ovat kooltaan suurempia ja niiden ohjattavuus on huonompi kuin kevyiden ajoneuvojen. Ne tarvitsevat enemmän aikaa, tilaa ja leveyttä kääntyessään päävirrasta rampille tai rampilta päävirtaan. Suomessa kaikkien raskaiden ajoneuvojen paitsi linja- autojen nopeusrajoitus on 80 km/h ja uusissa ajoneuvoissa on lisäksi nopeudenrajoitin.

Tutkimus perustuu kenttämittauksiin ja kirjallisuuteen. Tarkoituksena oli selvittää raskaiden ajoneuvojen vaikutusta korkealuokkaisten väylien liikennevirtaan ja samalla hankkia perustietoja HUTSIM-mikrosimulointiohjelman käyttöalueen laajentamiseksi korkealuokkaisten väylien simulointiin. Kenttätutkimusmenetelminä käytettiin rekisteritunnustutkimuksia videokameroilla sekä ajoneuvoseurantaa ja liikennevirrassa mukana ajoa instrumentoidulla ajoneuvolla. Lisäksi käytettiin liikenteen automaattisesta mittausjärjestelmästä (LAM) kerättyjä pistekohtaisia aineistoja.

Raskaiden ajoneuvojen kiihtyvyys ja hidastuvuus vaihtelivat välillä 1,1 - -1,1 m/s^2 ja kiihtyvyyshajonta oli pieni, kun instrumentoitu auto seurasi raskasta ajoneuvoa vakioetäisyydellä. Keskimääräinen nettoaikaväli edellä ajavaan raskaaseen ajoneuvoon oli 1,9 s juuri ennen ohitukseen lähtöä. Ohituksen jälkeen, kun ajoneuvo palasi omalle kaistalleen, takana olevaan raskaaseen ajoneuvoon jätettiin 1,4 s väli. Raskas ajoneuvo seurasi kevyttä ajoneuvoa suuremmalla nettoaikavälillä kuin kevyt ajoneuvo seurasi raskasta ajoneuvoa.

Keskimääräinen ajonopeus vaihteli välillä 84-91 km/h instrumentoidun auton seuratessa raskasta ajoneuvoa vakioetäisyydellä Hämeenlinnanväylällä (nop. raj. 120 km/h). Kehä III:lla (nop. raj. 80 km/h) välillä Isontammentie-Vanha Porvoontie keskimääräinen matkanopeus vaihteli välillä 60-81 km/h ja toiseen suuntaan välillä 62-80 km/h.

Raskaiden ja kevyiden ajoneuvojen matkanopeusero vaihteli välillä 4-13 km/h puolisuoralla rampilla ja oli noin 9 km/h silmukkarampeilla. Alamäessä raskaiden ja kevyiden ajoneuvojen matkanopeusero oli hieman suurempi kuin ylämäessä. Nopeusero vaihteli mäkisyyden ja nopeusrajoituksen mukaan. Nopeusrajoitusalueella 80 km/h raskaiden ajoneuvojen keskinopeus oli 3-5 km/h pienempi, nopeusrajoitusalueella 100 km/h 9-14 km/h pienempi ja nopeusrajoitusalueella 120 km/h 19-25 km/h pienempi kuin kevyiden ajoneuvojen keskinopeus. Raskaiden ajoneuvojen aiheuttama keskinopeuden aleneminen oli yleensä sitä suurempi mitä suurempi raskaiden ajoneuvojen osuus oli. Liikennemäärän kasvaessa peruskaistan keskinopeus aleni hieman nopeammin kuin ohituskaistan.

Jonossa ajavien ajoneuvojen määrä kasvoi liikennemäärän kasvaessa. Raskaiden ajoneuvojen osuus jonon johtajista oli suurempi kuin niiden osuus kaikista ajoneuvoista. Jonojen keskipituus kasvoi liikennemäärän ja raskaiden ajoneuvojen osuuden kasvaessa. Liikennemäärän vaikutus oli kuitenkin suurempi. Peruskaistalla jonon keskipituus kasvoi nopeammin kuin ohituskaistalla liikennemäärän kasvaessa.

Raskaille ajoneuvoille lasketut henkilöautoekvivalentit (Passenger Car Equivalents, PCE) olivat 1,7-7,2 rampeilla, 6,9-22,1 ylämäessä ja 3,2-4,7 alamäessä. Lasketut PCE-arvot olivat pienempiä nopeusrajoitusalueella 120 km/h kuin nopeusrajoitusalueilla 80 ja 100 km/h. PCE-arvot vaihtelivat eri palvelutasoilla ja myös eri kaistoilla.

Preface

This research work was commissioned by the Traffic Services unit of the Finnish National Road Administration to the Laboratory of Transportation Engineering of the Helsinki University of Technology and carried out based on a research plan made by Matti Pursula and Björn Silfverberg. The aim of the whole project is to develop a traffic flow simulation tool for high-class divided multilane highways by extending the microscopic traffic simulation program HUTSIM from traffic signal simulation to freeway simulation. The other parts of the project are "Kaistanvaihto moottoriteillä – kaistanvaihtomallit ja kenttätutkimus" (Lane-Change on Freeways - Lane-Change Models and Field Studies, Tielaitoksen selvityksiä 10/1998) and "Kehä III:n mikrosimulointimallin kehittäminen välille Ansatie-Kirkonkylä" (Development of microsimulation, case Ring III, Tielaitoksen selvityksiä 22/1998).

The data collection work for analysing the impact of heavy vehicles on Finnish freeway traffic flow was co-ordinated by M.Sc. Iiro Huttunen and the research work was carried out by M.Sc. Mohammed Shafiqul Mannan and M.Sc. Åsa Enberg under the supervision of Professor Matti Pursula. The other members of the project group were M.Sc. Mirja Noukka (Finnra, Traffic Services), M.Sc. Mari Ahonen (Finnra, Uusimaa region) M.Sc. Björn Silfverberg (LT-Consultants), M.Sc. Satu Innamaa (HUT), and student of technology Ville Lehmuskoski (LT-Consultants).

This study has been granted European Community financial aid in the field of Trans-European Networks - Transport (TEN-T).

Helsinki, May 1998

Finnish National Road Administration
Traffic Services

Alkusanat

Tämä selvitys on tehty Teknillisen korkeakoulun liikennelaboratoriossa Tielaitoksen Liikenteen palvelut -yksikön tilauksesta Matti Pursulan ja Björn Silfverbergin tekemän tutkimussuunnitelman "Mikrosimuloinnin kehittäminen, esimerkkinä Kehä III" pohjalta. Selvitys on osa "Korkealuokkaisten väylien mikrosimuloinnin kehittäminen" -tutkimusohjelmaa, jonka tarkoituksena on laajentaa HUTSIM-nimisen mikroskooppisen liikenteensimulointiohjelman sovellusaluetta moottoritiesimulointiin. Tutkimusohjelman muita tutkimuksia ovat mm. "Kaistanvaihto moottoriteillä - kaistanvaihtomallit ja kenttätutkimus" (Tielaitoksen selvityksiä 10/1998) ja "Kehä III:n mikrosimulointimallin kehittäminen välille Ansatie-Kirkonkylä" (Tielaitoksen selvityksiä 22/1998).

Tässä selvityksessä on tutkittu raskaiden ajoneuvojen käyttäytymistä ja vaikutuksia korkealuokkaisten väylien liikennevirtaan. Kenttätutkimukset suunnitteli ja toteutti dipl.ins. Iiro Huttunen ja selvityksen tekemisestä vastasivat dipl.ins. Mohammed Shafiqul Mannan ja dipl.ins. Åsa Enberg prof. Matti Pursulan valvonnassa. Projektin taustaryhmässä olivat mukana myös diplomi-insinöörit Mirja Noukka (Tielaitos, Liikenteen palvelut), Mari Ahonen (Uudenmaan tiepiiri), Björn Silfverberg (LT-Konsultit) ja Satu Innamaa (TKK) sekä tekniikan ylioppilas Ville Lehmuskoski (LT-Konsultit).

Selvityksen tekemiseen on saatu Euroopan unionin liikenteen perusrakenteen kehittämiseen tarkoitettua TEN-T (Trans-European Networks-Transport) -rahoitusta.

Helsingissä toukokuussa 1998

Tielaitos
Tiehallinto
Liikenteen palvelut

List of symbols

V	travel speed (km/h)
V_s	space mean speed (km/h)
$V_{average}$	average travel speed for a time interval (km/h)
V_{light}	speed of a light vehicle (km/h)
V_{heavy}	speed of a heavy vehicle (km/h)
$V_{15\%}$	15^{th} percentile speed (km/h), i.e. the speed level below which 15% of the vehicles are driving
$V_{85\%}$	85^{th} percentile speed (km/h), i.e. the speed level below which 85% percent of the vehicles are driving
σ_v	standard deviation of speed (km/h)
σ_a	standard deviation of acceleration (m/s^2)
V_{all}	space mean speed of all vehicles (km/h)
V_{free}	space mean speed of vehicles travelling at headways greater than 5 seconds
$V_{constraint}$	space mean speed of vehicles travelling at headway less than or equal to 5 seconds
HV%	percentage of heavy vehicles in traffic stream for a time interval
q	flow rate for a time interval (veh/h)
ϕ	convergence angle in degrees
H	hilliness (m/km)
D	dummy variables
PCE	Passenger Car Equivalent
a, b, c	estimated parameters
α, β, γ	estimated parameters
G	gap between two vehicles in seconds
N_{pl}	number of platooning vehicles

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1 BACKGROUND AND AIM OF THE STUDY

In real traffic control systems it is not always possible to execute field measurements and neither possible to make experiments with alternate schemes before decision making. Moreover, traffic is a large-scale system with many subsystems involving complex interactions. This complexity is influenced by vehicle fleet, size and sophistication of urban areas, which demands to develop a method or tool to handle the traffic system (Young et al. 1989). A method that is increasingly being used to solve these complex problems is the application of microcomputer simulation models. Computer simulation models are able to model these systems realistically and satisfactorily, which cannot be made in such a short time for as low a cost using other techniques (Young et al. 1989).

To evolve a microcomputer simulation model it is necessary to know interaction configurations, flow histories, road geometry, ramp geometry, and vehicle compositions on the road section in question. To validate and calibrate a simulation model with the real world large number of parameters are needed. These parameters can be estimated using extensive field measurements and reviewing literature. This work is part of a project with the aim to produce parameters to extend the microscopic traffic simulation program HUTSIM from traffic signal simulation to freeway simulation, which can be used as a supporting instrument to design freeways and to analyse the performance of the traffic flow.

The proportion of heavy vehicles in traffic flow is about 20 percent (20-30 percent on freeways and 10-20 percent on other main roads) in OECD countries (OECD 1983). In Finland the proportion of heavy vehicles in traffic flow fluctuates between 10 and 15% on average (Pesu 1996).

The impact of heavy vehicles on traffic flow has been investigated throughout the world in different ways for analysing capacity and level of service. This is because the level of service deteriorates as the number of trucks increases in traffic stream (Tan-Hw 1992). The capacity and level of service are not always adequate measures to document the traffic performance of an existing or proposed facility. These cases often involve complex geometric and signal control situations, oversaturated roads or ramps. Many large commercial vehicles are unable to negotiate small radius turns on ramps and compelled to slow down. This causes disturbance to other road users and reduces the overall speed level of other vehicles.

Heavy vehicles have a higher individual propensity to become platoon leaders than light vehicles (van Aerde & Yagar 1988). The lengths of the platoons increase when the platoon leader is a truck (Tan-Hw 1992). Heavy vehicles have operating capabilities that are inferior to those of light vehicles. On upgrades the impact of the inferior operating capabilities of heavy vehicles is extremely deleterious (Krammes & Crowley 1987). The effect of heavy vehicles (truck and truck with trailer) on nearby vehicles is of particular importance for certain roadway configurations, such as ramps and weaving sections, where lane changes are more frequent than on basic freeway sections.

This report concentrates on describing how the presence of heavy vehicles in the traffic stream makes perturbation to other vehicles in real traffic situations. The study is based on field measurements and literature review. Travel speeds of different vehicle types were collected using video cameras. Acceleration and car following gap were calculated based on data from an instrumented vehicle. Space mean speed, platooning, and passenger car equivalents were estimated from point measurement data. The idea is to make a systematic look at the effects of heavy vehicles on traffic flow on Finnish freeways and to develop adjustment factors for heavy vehicles for micro simulation purposes. It is well known that heavy vehicles have direct impacts on the traffic stream, but the quantifying of that impact has to be more precisely analyzed in real traffic situations.

2 REVIEW OF LITERATURE

2.1 General

It is well known that the impact of heavy vehicles on traffic flow is different from that of light vehicles. Heavy vehicles are generally large in size and the mechanical functions of these vehicles are different from those of other vehicle types. Mostly heavy vehicles have poor braking efficiency or loss of control at relatively low deceleration rates (SAE 1986). The stopping distance of an empty truck with trailer is much higher than that of a loaded one and almost double that of a light vehicle. The performance of a heavy vehicle is stable as long as the lateral acceleration does not exceed the peak level (SAE 1986). Rollover occurs when the lateral acceleration imposed on a truck exceeds the threshold that it can sustain. The lateral acceleration arises mostly from cornering and /or cross slope of the road (SAE 1986).

Because of better overtaking possibilities the impact of heavy vehicles in traffic flow is more temporary on multi-lane freeways than on two-lane. The probability of a light vehicle moving temporarily into another lane to overtake a heavy vehicle is nearly linear in relationship to the proportion of heavy vehicles per day on a highway. Heavy vehicles generally concentrate in the basic lane, and their impact on platoon formation decreases as the proportion of trucks in the traffic stream increases. However, the passenger car equivalent decreases as the proportion of trucks in the traffic stream increases (OECD 1983). The distribution of heavy vehicles on the road system is quite different from that of other vehicles. In Finland about 82% of the mileages driven by heavy vehicles are on public roads (Automobiles and Highways 1995).

In a study done in OECD countries it was argued that with a heavy vehicle speed limit of 80 km/h, roughly 40% of all trucks exceeded 80 km/h, about 10% exceeded 90 km/h, and about 5% exceeded 100 km/h. About 50% of the light vehicles exceeded 100 km/h (OECD 1983). In Finland the speed limit for all heavy vehicles except buses is 80 km/h and in new vehicles the speed is also technically limited to about 90 km/h using electronic equipment. With a truck speed limit of 80 km/h, about 50% of all trucks exceeded 80 km/h. About 7% of the trucks were driven with 10 km/h higher speed than the truck speed limit (Jakonen 1991).

2.2 Methods and data collections

The impacts of heavy vehicles on traffic flow have been investigated by collecting data regarding speeds, accelerations, headways, power, and mass of the vehicles. Spot speeds can be gathered using traffic analyzers with double induction loops or thin rubber tubes as detectors. Passing moment, headway, speed, vehicle type, and vehicle length can be recorded or calculated. The free speeds of vehicles have also been collected using road traffic radar (Archilla & Morrall 1994).

Travel speed of the vehicles can be collected using the license plate method. This method allows for the collection of a large amount of data and permanent data storage permitting further analysis of the data at any time (Seitti & Demarchi 1996). The license plate method has been used and the procedure has been described in many references (Enberg & Pursula 1997, Mason et al. 1990, Taylor et al. 1991, Kyte et al. 1991, Marler et al. 1994). The mass of the heavy vehicles can be measured automatically. The license plate number of the vehicles can be collected using tape recorder or video cameras. In Jakonen (1991) the engine power of the heavy vehicles was collected from the government computer centre based on the license plate numbers. Traffic delay caused by heavy vehicles was measured by travelling with a single articulated vehicle on various types of roads (OECD 1983).

In Francher et al. (1993) data for the relative motion of the leading vehicle was collected using an instrumented vehicle. A distance-measuring sensor installed at the front of the vehicle picked up the distance to the vehicle ahead. The rate of change of the distance was also measured. The performance of the vehicle system consisted of a heavy truck, sensors for measuring the motion of the leading vehicle, a cruise control modified to accept velocity commands, and a control unit for switching in and out of headway control mode. The procedure is described in detail in Francher et al. (1993).

The acceleration of a vehicle can either be measured directly by an accelerometer or approximated from a speed-time graph of the vehicle's trips (Drew 1968). Acceleration data can be collected using a mobile data acquisition system, which allows long time measurement at high sampling rate without any loss of data. The procedure is described in detail in Eismann & Schiehlen (1993).

2.3 Performance of heavy vehicles

The ability of heavy vehicles to avoid incidents is different than that of light vehicles. One of the main reasons is size and mass. Heavy vehicles need more space and width when turning from main stream to a ramp and vice versa. The road width required by a vehicle to negotiate a bend or corner varies with the design of the vehicle. Most heavy vehicles are steered by the front wheels except in the case of the articulated trailer, which is steered by the hinge point, while the rear wheels are fixed in the straight-ahead position. Many large heavy vehicles are unable to negotiate small radius turns while remaining within lane width. This can lead to conflicts with other vehicles travelling in the same direction (Brock 1973).

It is clear that the weight of the vehicle has an impact on speed. In Grate Britain it has been tested (Leonard et al. 1974) that though the heavy vehicles have similar mechanical properties, the vehicle with larger mass has lower speed than the vehicle with smaller mass. The vehicle weight does not have any remarkable impact on dynamic axle load. Generally the dynamic axle load of a heavy vehicle increases as the speed of the vehicle increases.

The braking force coefficient is just a conversion of vehicles' deceleration rate by taking into account the height of the centre of gravity. Williams et al. (1973) performed a study addressing changes in braking force coefficient as a result of road surface and types of tyres. They found that the braking force coefficient on wet surface and dry surface is different. Moreover, the braking force coefficient depends on the type of tyres. High value was observed when the heavy vehicle was driven using highway-service tyres and a much lower value was observed when the heavy vehicle was driven using smooth tyres. Very small differences were observed between tyres, when the vehicle was driven on rounded-gravel macadam (Williams et al. 1973).

The braking force coefficient (μ) of the heavy vehicle can be expressed in the following manner (Williams et al. 1973):

$$\mu = \frac{B_F}{R_F} = \frac{ml}{b+mh} \tag{1}$$

where:

B_F	= brake force from the two front wheels
R_F , R_R	= front and rear dynamic vertical reactions during braking (R_R can not be used for calculating braking force coefficients)
m	= vehicle longitudinal deceleration at the centre of mass in unit of (m/s^2)
l	= vehicle wheel base (a+b=l)
a	= distance of centre of mass behind front axle (m)
b	= distance of centre of mass in front of rear axle (m)
h	= height of centre of mass above ground (m)
W	= total vehicle weight (KN)

The symbols of *Equation 1* are presented in *Figure 1*. There were remarkable differences in both peak and locked-wheel braking force coefficients. Williams et al. (1973) found that the peak braking force coefficients were about 2-3 times higher than the locked-wheel braking force coefficients for all type of tyres. An example of the relationship between braking force coefficient and speed on mastic asphalt surface is illustrated in *Figure 2*. The braking force coefficient (peak and locked-wheel) of heavy vehicles on wet mastic asphalt surface fluctuated between 0.08 and 0.39, and on wet smooth concrete surface between 0.14 and 0.57.

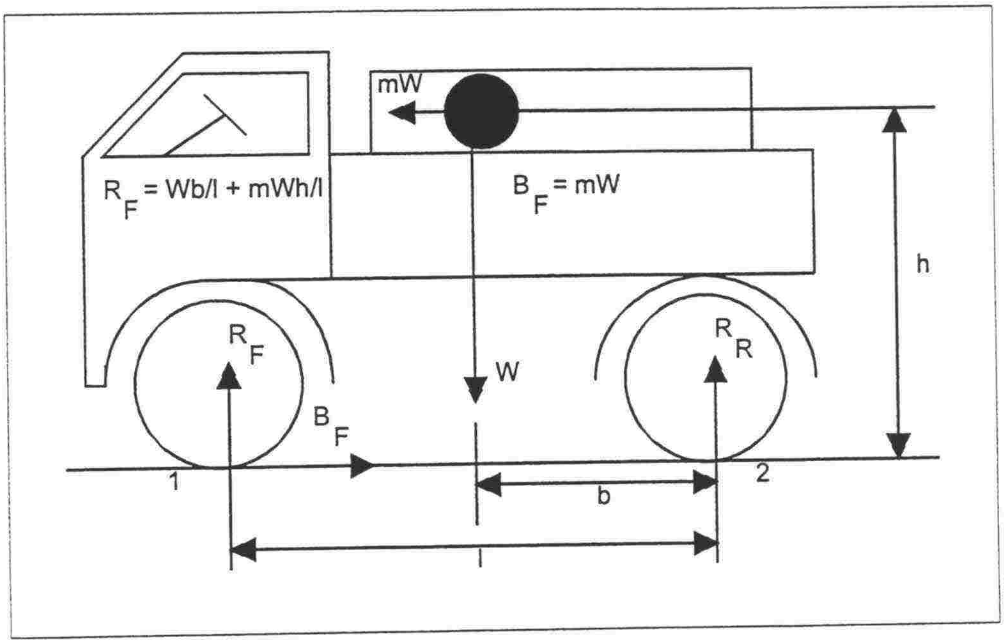

Figure 1. Sketch of a truck with symbols, which were used in Equation 1 (Williams et al. 1973).

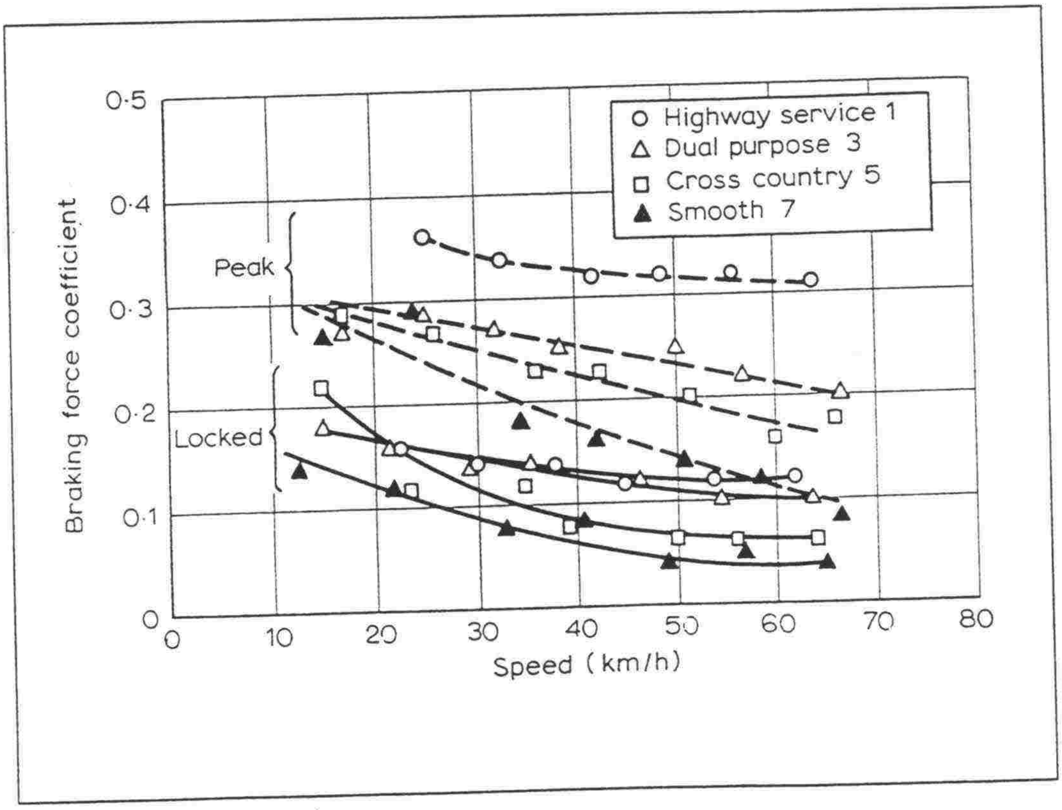

Figure 2. Braking force coefficient on wet mastic asphalt surface (Williams et al. 1973).

Trailer swing is the term used to express the condition of an articulated truck when the trailer behind the tractor unit is deflected from its correct line of travel during cornering. The trailer swing angle is illustrated in *Figure 3.*

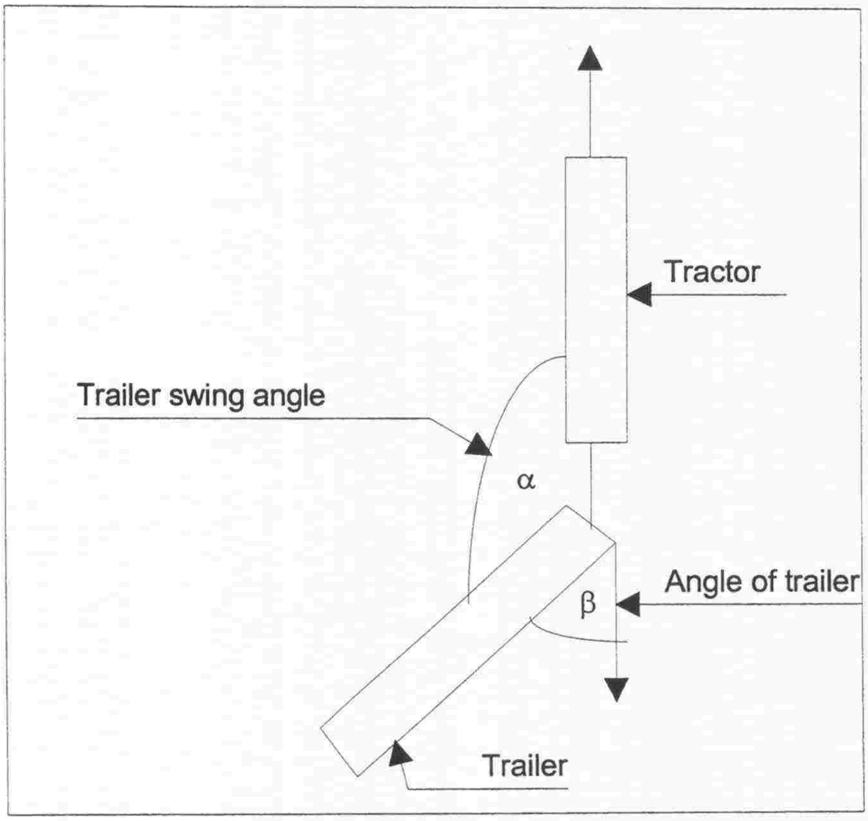

Figure 3. Conceptual diagram of a trailer swing angle.

The exact angle of swing for a vehicle depends on the dimensions and the centre of gravity of the trailer, the speed, the lateral and longitudinal accelerations and the coefficient of friction between the locked trailer wheels and the road. Though trailer swing has no effect on the stability of the tractor, it can be very dangerous for other road users. The trailer swing angle as a function of travel speed is shown in *Figure 4.* The angle through which the trailer swings relative to the tractor is dependent on the radius of curve and speed of the vehicle. The vehicle is compelled to slow down especially on ramps when the trailer swing angle of the vehicle decreases rapidly. The trailer swing angle increases as the speed of the vehicle increases. The trailer swing angles for different gradients and cambers of the road are almost exactly the same as the angles for the corresponding longitudinal and lateral accelerations. Trailer swing angle on a one in ten downhill gradient is almost the same angle as for 0.98 m/s^2 braking on the flat. At zero lateral acceleration the angle remains zero. The angle increases with increasing vehicle's braking decelerations and is proportional to the lateral acceleration (Chinn & Neilson 1972).

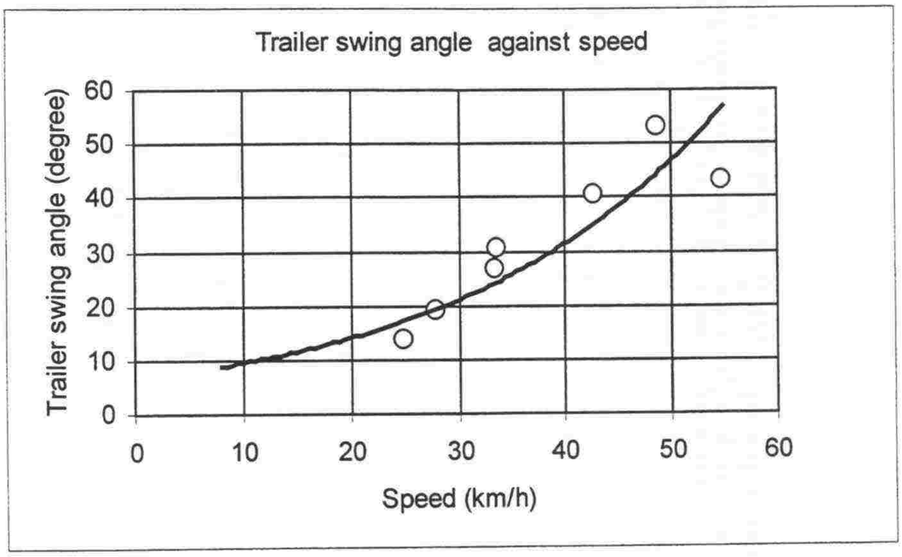

Figure 4. Trailer swing angle against speed when curve radius was 120 m (Chinn & Neilson 1972).

2.4 Braking philosophies

The brakes of a heavy vehicle are not as powerful, in relation to the loaded weight of the vehicle, as are those of a passenger car (Radlinski 1990). Moreover, it takes an appreciable time for the brakes to become fully applied after the driver has pushed the brake pedal, when the braking system is air operated.

In order to meet the requirements of the European Union, heavy vehicles must have large brakes on the steering axles and load-sensing proportioning valves on drive axles and trailer axles. Braking systems of heavy vehicles in the United States and in Europe are quite different. This is primarily due to differences in design criteria and in regulation. European heavy vehicles typically utilize more braking at the steering axle, and should exhibit superior braking efficiency under all loading and road surface conditions (Radlinski 1990).

A research work was done by the University of Michigan Transportation Research Institute to predict dynamic turning and braking behaviour based on computerized models. This analytical study used vehicle parametric data that was empirically determined. These phenomena were tested using empty trailers, half-loaded trailers, and fully loaded trailers. Straight-line stops, stops while turning, and stops while changing lanes were utilised as test maneuvers. The straight-line stops were performed on surface with uniformed coefficients of friction including dry concrete, wet polish concrete and wet Jennite-coated asphalt (Jennite is a brand of tar emulsion sealer commonly used to protect asphalt surface). The straight-line stops were also run on a split surface with the friction coefficient 0.7 utilising the wet Jennite and wet asphalt. The curve and lane change maneuvers were run only on the wet Jennite surface. For each test condition the driver made six stops and the stopping distances were stored in the computer memory. The braking efficiency was quantified based on the best stopping distance. The results of the experimental comparison between European and U. S. heavy vehicles indicate that European heavy vehicles should be able to stop in much shorter distance under all conditions mentioned above. These vehicles exhibit superior performance at both laden and unladen state at a 3.9 m/s^2 deceleration (Radlinski 1990).

2.5 Acceleration and deceleration

The acceleration and deceleration of a vehicle is a parameter and a good classification tool, which reflects the stability condition of the existing traffic stream and quantifies the smoothness of the existing traffic flow (Drew 1968). On a freeway with low traffic volume the maneuverability of a motorist is not restricted by other motorists. He may accelerate and decelerate occasionally and deviate from a uniform speed during his journey without awareness. If we assume that acceleration is constant, then the relationship between speed (v) and acceleration (a) can be expressed in the following manner:

$$\frac{dv}{dt} = a \qquad (2)$$

The acceleration of a vehicle at time t_i can be denoted by $a(t_i)$. If $v(t_i)$ and $a(t_i)$ are the speed and acceleration of a vehicle at time t_i, then the average acceleration of a vehicle for a trip of time T can be written as follows (Drew 1968):

$$a_{average} = \frac{1}{T}\int_0^T a(t_i)dt = \frac{1}{T}\left[V(T) - V(0)\right] \qquad (3)$$

The average acceleration rate is a rather important parameter (Drew 1968). The acceleration of the platoon leader has a direct effect on the discharge of platoons and on capacity. The average deceleration rate is also an important parameter for evaluating car-following distance (Kosonen 1996). Many factors are related, directly and indirectly, to this parameter. These factors are the friction between tyres and road surfaces, vehicle composition on the lane, vehicle type, weather condition, and vehicles' characteristics.

Niittymäki & Pursula (1994) have studied the dynamic behavior of traffic at signalized intersections. The vehicle parametric data used in this study was empirically determined. According to the results the rate of the acceleration and deceleration varies due to vehicle type. Heavy vehicles have clearly lower acceleration rates than passenger cars. The maximum momentary deceleration rate of a light vehicle was 6-7 m/s^2 and of a heavy vehicle 5 m/s^2. However, in reality such high values of decelerations are not recognised. The average acceleration and deceleration rates for different vehicle types are shown in *Table 1*. These values were procured for the HUTSIM microcomputer simulation program.

Table 1. Acceleration and deceleration based on vehicle type (Kosonen 1996).

Parameter	Car	Truck	Bus	Truck with trailer	Unit
Average acceleration	1.6	1.2	1.0	1.1	m/s^2
Average deceleration	1.9	1.7	1.2	1.5	m/s^2
Maximum acceleration	3.2	3	2.0	2.6	m/s^2
Maximum deceleration	2.2	1.6	1.4	1.5	m/s^2
Vehicle length	4.0	7.0	12.0	18.0	m

A fully laden heavy vehicle requires nearly double the distance what a passenger car requires to stop. Moreover, mostly a passenger car can reach an overall average deceleration of 7.9 m/s^2 throughout a braking stop, whereas a laden heavy vehicle does not reach much above 3.9 m/s^2. The weight and number of axles of the vehicles also have direct impact on acceleration. Maximum ground acceleration varied between 0.20 m/s^2 and 0.59 m/s^2 when the speed of the vehicle was around 70 km/h (SAE 1986).

In a study done in United States, Mason et al. (1993) analysed truck operational characteristics related to intersection sight distance. In this study the minor road was associated with a truck generator (with a high percentage of truck traffic) and both the major and minor roads were two-lane roads meeting as a T -intersection. The minor road was controlled by a stop sign. The speed limit for the major road in the vicinity of the intersection was 70 km/h. The deceleration rate and speed reduction occurring before the intersection for vehicles of the major road reacting to 5 axle trucks turning from the minor road were determined. These values typically represented a 61 to 122 m total deceleration distance ending 15 to 46 m before the intersection. *Table 2* presents the deceleration rates and speed reduction values. The 15^{th} and 85^{th} percentile deceleration rates were 1.64 and 2.6 m/s^2, and the speed reductions were 35.7 and 61.3 km/h, respectively (Mason et al. 1990).

Table 2. Deceleration rate and speed reductions for light vehicles on the major road reacting to five-axle trucks turning from the minor road (Mason et al. 1993).

	Deceleration rates	
	50^{th} percentile	85^{th} percentile
Deceleration Rate	1.64 m/s^2	2.6 m/s^2
Speed Reduction	35.7 km/h	61.3 km/h

The acceleration rates for heavy vehicles completing left and right turn maneuvers were calculated using average velocities and average time required to traverse a given distance. The time at which an accelerating truck left the intersection and arrived at each 31 m increment line were read from the clock superimposed on the video tapes. These times were recorded in a computer spreadsheet program in hours, minutes, and seconds. In order to analyze the vehicles' distance-versus-time curves, and acceleration rate, the raw data were standardized so that all vehicles left minor road at time zero. The heavy vehicles were equipped with 3 to 5 axles (Mason et al. 1993). *Table 3* presents a summary of the average acceleration rates.

Table 3. Average acceleration rates for heavy vehicles (Mason et al. 1993).

Turn maneuver	Truck type No. axles	Distance of acceleration (m)	Acceleration rates	
			50^{th} percentile	85^{th} percentile
Left	3 & 4	0-89	0.57 m/s^2	0.71 m/s^2
Right	3 & 4	0-150	0.47 m/s^2	0.54 m/s^2
Right	5	0-107	0.36 m/s^2	0.54 m/s^2
Right	5	0-156	0.59 m/s^2	0.78 m/s^2

As can be seen from *Table 3* the 50^{th} percentile average acceleration rates ranged from 0.36 to 0.59 m/s^2 and the 85^{th} percentile average acceleration rates from 0.54 to 0.78 m/s^2.

2.6 Gaps

In car following state the gap is the distance between two moving vehicles from the rear bumper of the leading vehicle to the front bumper of the following vehicle. The units may be those of either time or distance. The time headway of the following vehicle is the difference between the rear bumper passage moment of the leading vehicle and the rear bumper passage moment of the following vehicle. From the traffic flow point of view time headway is more important because the reciprocal of mean headway is equal to the flow rate.

The gap is usually more meaningful to the driver than the time headway. The gap can be directly related to the perception-reaction time of the following driver in response to abrupt changes in the speed of the leading vehicle. In the barest sense, a safe and sufficient gap is a function of the relative and absolute speed of the vehicles involved, driver reaction time, braking distance, roadway conditions, the presence of traffic, visibility, and road geometry. Marshall et al. (1998) performed one of the most recent studies addressing changes in headways as a result of environmental influences and drivers' behaviors. According to the study the gap between two vehicles varies with roadway characteristics and traffic conditions. The presence of congestion may also influence gap selection, with higher traffic densities leading to shorter gap. In a freeway cross-section at high densities (97-145 veh/km) the average gap varied between 0.5 and 0.8 seconds (Marshall et al. 1998).

There are two types of gaps in the traffic stream, gaps between platooning vehicles and gaps between the platoons. The gaps between platooning vehicles can be denoted as inter platooning gaps and the gaps between two platoons can be denoted as intra platooning gaps. A vehicle can freely enter the main stream from a ramp during gaps occurring between platoons. On the other hand, a vehicle can or can not enter the main stream during gaps within a platoon depending on platoon criteria (Tsao et al. 1997).

The gap that a driver accepts (gap acceptance) in the traffic stream depends on the traffic situation in question, speed limit of the sections, and the behavior of the driver of the leading vehicle. The gaps when leaving a platoon are different from the gaps when merging a platoon. The gaps of the followers in a platoon also vary. Setti & Demarchi (1996) studied the impact of heavy vehicles on operation of rural intersections in Brazil. Data were used for estimating gaps and capacity. All intersections had similar geometric design features. It was found that the gap acceptance of a truck with semi-trailer varied between 2 and 22 seconds and of a truck with full trailer between 8 and 32 seconds (Setti & Demarchi 1996).

The gaps that drivers accept at a ramp also depend on the shape and geometry of the ramp. About 50 percent of the drivers accept gaps less than 1.5 seconds at an entrance ramp with a 3° angle of convergence and less than 3.5 seconds at an entrance ramp with an 11° angle. (Drew 1968)

According to Marshall et al. (1998) tailgating vehicles are mostly both passenger cars or both trucks in real traffic situations. This could be expected due to the fact that drivers of passenger cars are able to see beyond other passenger cars but not trucks. Passenger cars are usually not tailgating trucks, if they are not forced to (Marshall et al. 1998). Based on a Canadian study the mean gap size accepted by motorists before overtaking was 17 seconds when impeded by a passenger car, compared to 39 seconds when impeded by a 30 meter long truck. About 70% of the drivers impeded by passenger cars accepted a gap size of 25 seconds. Compared to this, 70% of the drivers accepted a 50 seconds gap size when impeded by a truck (Barton & Morrall 1998).

To clarify existing car following behaviour with respect to traffic flow regimes an empirical study was carried out in the Netherlands (Dijker et al. 1998). Based on the Dutch study, the distance gaps (in meter) of passenger cars are longer in congested flow than in non-congested flow at the same speed level. The differences in distance gaps between the two regimes are the largest on the median lanes and the smallest on the shoulder lanes. For trucks no differences between the regimes were found. The overall distance gaps between two vehicles increased as the speeds of the vehicles increased (Dijker et al. 1998).

2.7 Effects of road geometry

For evaluating the effects of any geometric feature, some traffic variables or parameters have to be measured and compared for different geometric conditions. According to Drew (1968) the speed change between the nose and merging point could be a good indicator of the effect of different ramp geometries in the case of a freeway entrance ramp. A vehicle, which wants to enter a ramp has to stop or slow down and again to accelerate to adjust its speed to the speed of the freeway. At poorly designed ramps, many vehicles will be forced to stop or travel very slowly at the nose while selecting a gap and will then have to accelerate rapidly in an attempt to approach the freeway speed. At the nose of the ramp, small convergence angles provide the opportunity to maintain high speed. The share of slow ramp vehicles increases quite rapidly with an increase in the convergence angle. On ramps with acceleration lanes exceeding 290 m, about 85 percent of all drivers passed the nose at speeds greater than 48 km/h. The speed is obviously more uniform on ramps with a long acceleration lane than on ramps with a short acceleration lane. (Drew 1968)

Kanellaidis et al. (1990) performed a study addressing speed behavior on horizontal road curves using data from 58 curve sites. The relationship between operating speed and various geometric design parameters, namely radius of curve, superelevation rate, lane width, shoulder width, and length of the curve, were investigated. The results suggested that the operating speed is strongly related to the bendiness of the road section. The rate of change of operating speed decreases as the bendiness (deg/km) decreases.

Andjus & Maletin (1998) have performed one of the most recent studies addressing reduction of vehicle speeds for different radii of horizontal curves. This pilot research work has been undertaken by considering a number of horizontal curves with a radius ranged from 50 m to 750 m. They found that the speeds of the vehicles increased with radius of curves. The speeds varied between 42 and 73 km/h when the radius of the curve was 70 m and between 59 and 100 km/h when the radius of the curve was 360 m.

Mintsis (1990) studied speed distributions on road curves and found that the variation of speed is highly dependent on the curvature (total change in direction per unit distance) of the road. For high curvature values the speeds were found to vary considerably. Remarkable speed changes were observed when the radius of the curve changed from 100 to 200 m. For passenger cars the level of approach speed has less effect than for heavy vehicles. This is because most heavy vehicles made speed adjustments when approaching the curve. The overall speed in the middle of the curve was found to be lower than the speed when approaching or exiting the curve. The speed of a heavy vehicle at the exit location was about 23% lower than that of a light vehicle. This is because the acceleration rate of a passenger car is higher than that of a heavy vehicle. Speeds of light vehicles and heavy vehicles on a road curve according to Mintsis (1990) are shown in *Table 4*.

Table 4. Speed of the vehicles (km/h) on a road curve (Mintsis 1990).

Speed Parameter	Light vehicle			Heavy vehicle		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Approach	76	110	95.4	68	87	77.9
Entry	69	111	92.2	52	89	74.4
Middle	57	107	87.1	48	86	69.3
Exit	67	115	91.5	52	88	71.5

According to Hall et al. (1994) passenger car speeds are increased by hilliness falls, and decreased by rises greater than 40 m/km. Simultaneously the speeds of the heavy vehicles are effected by hilliness rises. According to a Finnish study from 1973 (Roine 1973) the average speed of a heavy vehicle decreased by 2.05 km/h when the hilliness (changes in elevation in meter per kilometer) increased by 10 m/km. The relationship between mean speed of heavy vehicles (km/h), lane volume Q (veh/h), hilliness (M, m/km) and curvature (K, deg/km) was expressed using the following regression model:

$$V_{heavy} = 77.32 - 0.00241 \times Q - 0.205 \times M - 0.0087 \times K \quad R^2 = 0.25 \qquad (4)$$

According to Archilla & Morrall (1994), a driver is not generally be free to modulate speed on a severe downgrade because it is usually impractical or dangerous to shift down. There is a great variation in speed with the steepness of the downgrade. This variation can in general be attributed to a behavioral response and for trucks it can also be attributed to a difference in braking capabilities for different truckloads. Archilla & Morrall (1994) have reported that the speeds for light vehicles, trucks and buses were 3.5 km/h higher on sections with 4.45% downgrade than on sections with 6.51% downgrade. The speed of the heavy vehicles after the end of a gentle (not severe) downgrade was higher than the speed for level sections. This is because the truck drivers let their vehicles accelerate before the end of the grade is reached. However, on the steepest downgrades, they maintained lower speeds almost from up to the bottom of the grade. Average speeds of different vehicle types on level sections and on downgrades are shown in *Table 5*.

Table 5. Average speed and standard deviation of speed of different vehicle types on level road sections and on steep downgrades (Archilla & Morrall 1994).

Vehicle Type	Level sections		Downgrades (6.51%)	
	Average speed (km/h)	Standard Deviation (km/h)	Average speed (km/h)	Standard Deviation (km/h)
Passenger car	98.42	8.16	91.45	10.09
Recreational Vehicle	95.18	6.44	83.40	9.87
Single Unit Truck	95.75	7.71	79.52	11.67
Semitrailer	96.01	5.44	72.11	15.86
Combination	93.26	5.94	58.45	15.74
Bus	95.50	4.89	79.18	9.55
All	97.64	7.84	86.97	13.62

2.8 Traffic volume, vehicle types, and platooning

It is well known that there is an effect on speed because of traffic volume and type of the vehicles. The traffic volume varies with time and road type. However, the composition of vehicles also has day-to-day and seasonal variations (Traffic and Roads I 1987). Especially heavy vehicles have direct impact on traffic flow and speed level. Usually heavy vehicles are large in size, their acceleration rate is low, and their braking system is different than that of light vehicles (HCM 1994). Mostly heavy vehicles are not able to maintain the same speed level as light vehicles, which reduces the capacity of the road section and forms platoons.

The impact of flow rate and proportion of heavy vehicles on speed has been investigated widely. One study was concluded by Botma (1994) using data of T-intersections situated on two-lane rural roads. An earlier study concluded by Botma (1986) was using data of two-lane busy roads. The influence of the presence of heavy vehicles on mean speed was expressed using linear regression analyses. The mean speed on a lane is related to the volume and truck percentage. Only volume and truck percentages of the same direction had a linear influence on mean speed. Over the lane volume range of 300 to 1,100 veh/h, mean speed decreased on the average 10 km/h. The mean speed decreased about 5 km/h, when the range of truck percentage changed from 5 to 30 percent.

In a study reported by Hall et al. (1994) the relationship between speed and flow in U.K., Germany and North America was analysed. The number of trucks was converted to passenger car units using a truck equivalence factor of 2.0. A piecewise linear regression was used to evaluate the relationship between speed (V) and flow rate (Q) at different proportion of trucks. The fitted linear functions were as follows:

$$V = 123 + 16 \times D - 0.0193 \times D \times Q \qquad R^2 = 0.81 \qquad (5)$$

where D is 0 below 700 pcphpl and 1 above that value.

$$V = 128 + 30 \times D - 0.0109 \times Q - 0.0192 \times D \times Q \qquad R^2 = 0.84 \qquad (6)$$

where D is 0 or 1 below or above 1500 pcphpl.

$$V = 124 - 0.007 \times D1 \times Q + 35 \times D2 - 0.023 \times D2 \times Q \qquad R^2 = 0.84 \qquad (7)$$

where D1 is defined on 600 pcphpl and D2 on 1,500, each variable being 0 below and 1 above that value of flow respectively.

Based on U. K. data (Hall et al. 1994) the slope of the regression equation depends on percentage of heavy vehicles in the flow. In a two segment piecewise linear function (breakpoint 1,200 vphpl), the slope for passenger cars is –6 km/h per 1,000 vphpl in the first segment. For heavy vehicles there is no effect of increased flow within the first segment. In the second segment, the effect of the passenger cars is –27 km/h per 1,000 vphpl, while the slope for heavy vehicles is –14 km/h per 1,000 vphpl.

According to Highway Capacity Manual (HCM 1994) a vehicle can be considered as belonging to a platoon if the time headway to the preceding vehicle is less than 5 seconds. Different studies use different measures regarding platoon criteria. No unique definition of platoon has been defined, yet. Radwan & Kalevela (1985) and Rozic (1992) did not consider a vehicle belonging to a platoon if headways exceed 9 seconds. Keller (1976) used headways less than 2 seconds as a platoon criterion. Guell and Virkler (1988) proposed that meaningful results can be obtained by using 3.5 and 4 seconds as platoon criteria. Pursula & Enberg (1991) used 5-second time headway as platoon criterion. According to the definitions platoon leaders do not belong to the platoon. A platoon is formed by a platoon leader and one or more following vehicles. Platoon leaders are those vehicles which are unimpeded and followers are the impeded vehicles. According to Archilla & Morrall (1994) the maximum observed platoon size and mean platoon size tend to increase with increasing volume when a 5-second headway is used as a platoon criterion. The proportion of passenger cars leading a platoon is lower than the proportion of passenger cars in the traffic stream. On the other hand the proportion of heavy vehicles leading platoons is greater than the proportion of these same vehicles in the traffic stream. The length of the platoon is shorter when a light vehicle is the leader of the platoon than when a heavy vehicle is the leader of the platoon (Jakonen 1991).

There is a linear relationship between the number of platoons and daily traffic volume. The number of platoons increases by 40 as the number of heavy vehicles increases by 100 veh/day and by 230 as the traffic volume (heavy and light) increases by 1,000 veh/day (Pesu 1996).

There is an exponential relationship between the proportion of platooning vehicles and traffic volume for different truck percentages. In the study concluded by Botma (1986) data of two-lane busy roads were used. The influence of the presence of heavy vehicles on platooning was expressed using regression analyses. It was found that the lane volume (Q) and the truck percentage (TP) of the flow considered gave the most satisfactory model. The models were developed based on traffic data including 12-24% heavy vehicles and the speed limits of the study sections were 80 and 100 km/h. The proposed models (Botma 1986, 1994) are as follows:

$$PRHN = 1 - e^{(-0.0017\,q - 0.0067\,TP)} \qquad R^2 = 0.77 \quad (8)$$

$$MEXLEN = 2.90\, e^{(0.0018\,q + 0.0040\,TP)} \qquad R^2 = 0.64 \quad (9)$$

where PRHN is the proportion of the hindered vehicles, MEXLEN is the maximum length of the platoon, q is traffic volume (veh/h) and TP is truck percentage. According to these models the impact of heavy vehicles on platooning decreases as the traffic volume increases.

2.9 Passenger car equivalents

Passenger car equivalents (PCE) have usually been used for analyses of capacity and level of service. There have been numbers of efforts to determine PCE values for various conditions, but most of these have focused on recalibrating the methods outlined in the HCM. Though it is assumed that the car following behavior in platoons is representative for capacity and consequently the PCE definition is based on a comparison of headways of trucks and cars in platoons (Botma 1994). Two basic principles should be applied for the estimation of PCE values for any of the road types identified in capacity analysis procedures. The first one is PCE values for the level of service (LOS) estimation and the second one is the consideration of factors that contribute to the overall effect of trucks on traffic stream performance (Krammes & Crowley 1987).

The review of literature indicated that there is no universal PCE value that can be used for all purposes (Botma 1994, Krammes & Crowley 1987, van Aerde & Yagar 1988, Setti & Demarchi 1996, OECD 1983, Mahmassani & Kim 1988). The PCE value varies according to the geometry of road, lane type and merging and diverging sections. The HCM recognizes only two geometrical factors, grade and terrain, but no other geometrical features such as those encountered in sections for merging or diverging. For most flat to intermediate downgrades passenger car equivalents and truck factors can be considered the same as those on level ground without appreciable error. On heavy downgrades, however, where trucks descend with a low gear for safety, special consideration may need to be given (HCM 1994).

The operating conditions on a highway are divided into six levels, A - F. The PCE values vary according to the operation conditions of the highway. Though the capacity analysis procedures are calibrated for a specific set of ideal conditions, adjustments are made for deviation from those ideal conditions; the adjustment factor for the presence of trucks is based on PCEs. On freeways the PCE values increase with flow rate (Krammes & Crowley 1987). *Table 6* presents the PCE values on level freeway segments.

Table 6. PCE values for trucks on level freeway segments (Krammes & Crowley 1987).

Lane	Level of Service A Q = 700 veh/h	 B Q = 1,100 veh/h	 C Q = 1,550 veh/h
Right	1.2	1.6	2.0
Center	0.9	1.1	1.2
Left	1.8	2.1	2.6
All	1.0	1.2	1.2

As in the OECD countries (OECD 1983) the passenger car equivalent decreases as the fraction of trucks in the traffic stream increases on freeways in the United States. According to a Canadian study (van Aerde & Yagar 1988), PCE values are larger for low volume rates than for high volume rates. It was proposed that there is no unique value of PCE, neither any particular system for estimating PCE values. In the Canadian study the PCE values were estimated in terms of speed reduction parameters and in terms of platoon leaders and followers. The estimated PCE values are illustrated in *Table 7*.

Table 7. Average generalised PCE values (van Aerde & Yagar 1988). Low volume: 0- 650 veh/h, High volume: 650-2000 veh/h.

Vehicle Type	Speed Equivalents 10th percentile	 50th percentile	 90th percentile	Platooning Equivalent Followers Low Volume	 High volume	 Leaders
Truck	11.4	6.1	3.8	1.23	1.2	2.0
Recreational	3.9	3.7	2.6	1.23	1.07	1.55
Light vehicle	1.0	1.0	1.0	0.98	1.13	1.46

3 RESEARCH METHODS AND MATERIALS

3.1 General

The use of traffic simulation models is a method worth consideration when evaluating traffic performance measures in the laboratory stage. Traffic simulation is an attempt to use computer algorithms to model the evolutionary process before decision making. To develop microscopic simulation it is necessary to procure information regarding interactions between vehicles, vehicles and pedestrians, traffic control systems, and road conditions for the modelling process. It is necessary to gather a versatile information regarding the relationships between different characteristics like vehicle speed, vehicle composition, road geometry, weather effect, lane changing process, controlling system, etc. to imitate the situation in the laboratory stage (Pursula & Silfverberg 1997). This information can be gathered by empirical field measurements and theoretical review. The gathered information is then used to develop simulation models and to calibrate and validate them to the real world.

In order to quantify the impact of heavy vehicles and at the same time to procure parameters for the Finnish HUTSIM simulation model quite extensive field measurements were carried out in late summer 1997. Information on travel speeds on grades was collected using the license plate method on three different divided multilane highways (Turunväylä, Hämeenlinnanväylä and Ring Road III). Information about travel speeds on ramps was also gathered with the license plate method on several divided highways. Ring Road III is a divided multilane highway with speed limits 70/80 km/h and the highway section in question is partly signal controlled. Turunväylä and Hämeenlinnanväylä are freeways with speed limits 100/120 km/h. Information about point speed on different freeways and divided multilane highways was gathered from Automatic Measurement System of the Finnish National Road Administration. To observe the variations in behaviour between drivers and differences in the accelerations and decelerations of vehicles an instrumented vehicle was driven in the traffic stream on Ring Road III and on Hämeenlinnanväylä.

3.2 License plate studies

Data for travel speed and travel time were collected using S-VHS video cameras, which were placed in successive locations on different ramps and on upgrades and downgrades. The map of the measurement locations is given in *Appendix A*. The registration number, vehicle type, and passing time for each vehicle were observed from a video monitor screen and entered into PC data files. The data files were analyzed with special computer programs to get the following information in 5-minute intervals:

- traffic flow on the highway section
- proportion of heavy vehicles

- average travel speed and travel time of each vehicle type
- cumulative distribution of speed for each vehicle type
- 85 percentile speeds
- 15 percentile speeds.

3.3 Moving observation car mesurements

Data were collected on Hämeenlinnanväylä by the moving observation car method using an instrumented vehicle. A laser-operated distance measurement instrument (laser radar) was mounted close to the front window inside the test vehicle and connected to a portable computer. A speed sensor was used to measure the speed of the test vehicle. The travel time, travel distance, speed of the test vehicle, and the distance between the test vehicle and the vehicle in front of it were stored in the computer memory. The system measured and stored the data per second basis. Moreover, a number of manual codes was used to specify detailed information regarding overtaking and lane changing behavior of heavy vehicles. The data were gathered using test drivers and by observing the behaviour of other drivers. The data analyses were concentrated on the behaviour of heavy vehicles. The gaps just before overtaking the heavy vehicle and just after the overtaking of the heavy vehicle were calculated. Some measurements were also done on Ring Road III without the laser radar to get some information about the speed level on a partly signal controlled section. The map of the measurement locations is given in *Appendix A*.

3.4 Car following measurement

The instrumented vehicle was used to perform some measurements by following heavy vehicles on a section of Hämeenlinnanväylä (see map in Appendix A). The instrumented vehicle was following randomly chosen heavy vehicles at a constant distance of about 40 meters. Information about speed and observed overtakings were recorded. The acceleration and deceleration rates were calculated based on speed changes of the test vehicle in response to the heavy vehicle.

3.5 Point measurements

The point measurement data were collected from the automated traffic measuring system (LAM) of the Finnish National Road Administration (Finnra). Collected data were analyzed with special programs to give mean speeds, flows, time headways, platoon lengths and platoon percentages. The results presented using point measurement data are based on 15-minute intervals.

4 ACCELERATION AND DECELERATION

4.1 Acceleration and deceleration rate

The average acceleration and deceleration rates were calculated from the speed data collected by the instrumented vehicle when following a heavy vehicle on Hämeenlinnanväylä and when driving on Ring Road III trying to float with the other traffic. The calculation procedure was very simple by using the velocity and time required to traverse a given distance. The speed limit on Hämeenlinnanväylä was 120 km/h. Six measurement trips between Keimola and Hyvinkää on Hämeenlinnanväylä and five measurement trips between Vanha Porvoontie and Isontammentie on Ring Road III were evaluated.

The lengths of the investigated road sections were 30 km between Keimola and Hyvinkää and 13.3 km between Isotammentie and Vanha Porvoontie. It might be supposed that if the speed of the vehicle does not change within two successive seconds then the acceleration of the vehicle is zero. Similarly, it might be supposed that when the speed decreases or increases within two successive seconds then the vehicle decelerates or accelerates, respectively.

The acceleration rate on Ring Road III fluctuated between 0 and 2.9 m/s^2 when the test vehicle was driven throughout the traffic stream. The deceleration rate of the test vehicle on Ring Road III fluctuated between 0 and –3.5 m/s^2 (*Appendix B*). The acceleration rate (here representing the heavy vehicle) on Hämeenlinnanväylä fluctuated between 0 and 1.1 m/s^2 and the deceleration rate fluctuated between -0 and –1.1 m/s^2 when test vehicle followed a heavy vehicle at a constant distance of 40 meter. The acceleration and deceleration rates when following the heavy vehicles are shown in *Figure 5.*

The distribution of acceleration and deceleration rates when the test vehicle followed a heavy vehicle at a constant distance of 40 meter on Hämeenlinnanväylä is shown in *Figure 6.* Average, 15th percentile, 50th percentile and 85th percentile acceleration rates and standard deviations of acceleration are shown in *Table 8* and they were calculated from the whole data set. Similarly, frequency and cumulative distributions of the acceleration and deceleration were calculated by combining the data of both directions.

Table 8. Average acceleration rate of the test vehicle when following a heavy vehicle at a constant distance.

Hämeen-linnanväylä	$a_{15\%}$ m/s^2	$a_{50\%}$ m/s^2	$a_{85\%}$ m/s^2	Average m/s^2	σ_a m/s^2	Number of observation
Acceleration	0	0.18	0.41	0.33	0.14	3326
Deceleration	0	-0.08	-0.31	-0.31	0.14	3331

Based on the analyses it can be noticed that the 50th and 85th percentile acceleration rates were much higher than the 50th and 85th percentile deceleration rates. There was little difference between the average acceleration and deceleration rate of the test vehicle when following a heavy vehicle. This means that the accelerations and decelerations were uniform when test vehicle followed a heavy vehicle. The standard deviations of accelerations and decelerations of the whole data set did not vary much.

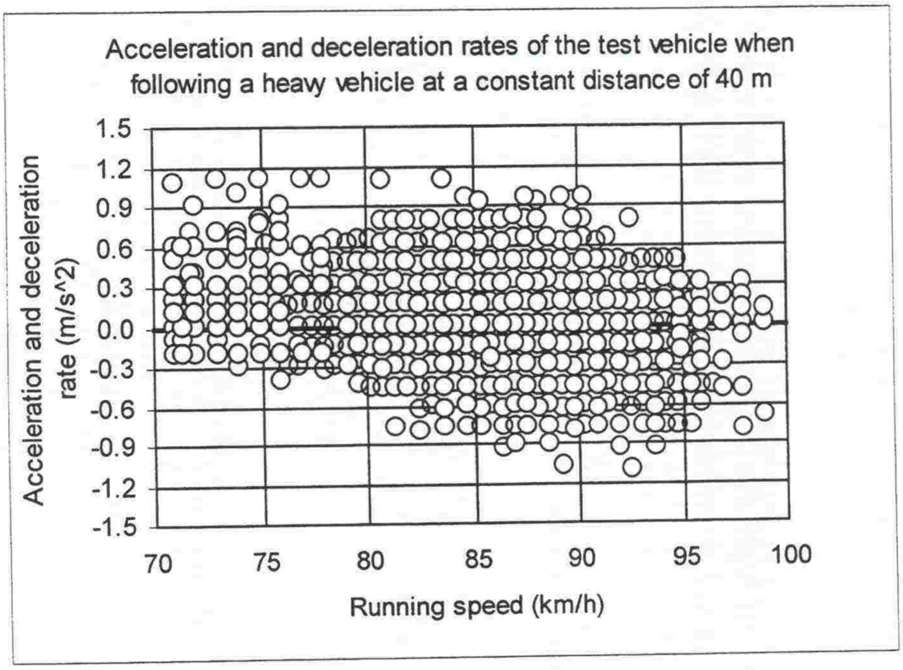

Figure 5 . Acceleration and deceleration rates of the test vehicle when following a heavy vehicle at a constant distance (40 m).

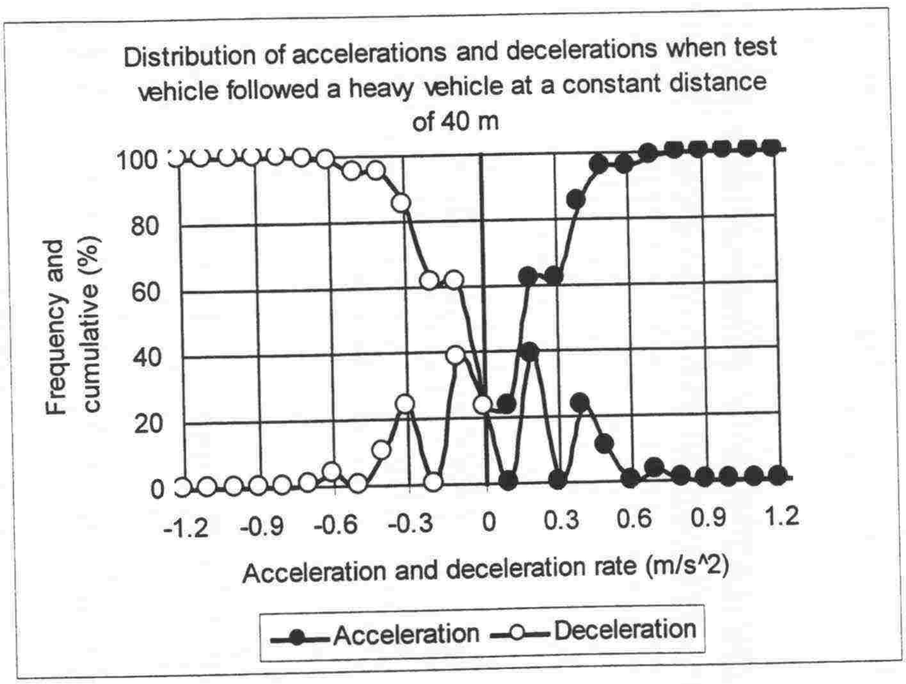

Figure 6. Distribution of accelerations and decelerations when test vehicle followed a heavy vehicle at a constant distance (40 m).

4.2 Acceleration noise

The smoothness of the journey can be measured by determining the standard deviation (σ_a) of the accelerations. This standard deviation of the acceleration is known as acceleration noise. Acceleration noise seems to be a useful parameter in helping to evaluate the behaviour of various drivers in a traffic stream in terms of traffic safety (Drew 1968).

The accelerations can be considered as random components of time, and the distribution essentially follows the normal distribution. The acceleration noise varies with the amount and frequency of acceleration and deceleration. According to Drew (1968) acceleration noise (σ_a) of a vehicle is 0.10 m/s^2 when the speed of the vehicle is changed from 32 km/h to 97 km/h. However, these values fluctuate between 0.24 and 0.43 m/s^2 on a country road.

Congestion is an important factor, which directly influences the amount of acceleration noise. The noise increases when congestion increases because of higher traffic volume. In Drew (1968) the noise during off peak period is 0.24 m/s^2 and during peak periods 0.43 m/s^2. As mentioned before the acceleration noise (σ_a) is the standard deviation of the acceleration of the traffic stream and it can be written in the following manner (Drew 1968):

$$\sigma_a = \left\{ \frac{1}{T} \int_0^T \left[a(t_i) - a_{ave} \right]^2 dt \right\}^{\frac{1}{2}} \qquad (10)$$

where,

σ_a = acceleration noise (m/s^2)
$a_{(ti)}$ = acceleration at time t_i (m/s^2)
a_{ave} = average acceleration (m/s^2).

By taking the square of both sides of the equation the expression can be written in the following manner:

$$(\sigma_a)^2 = \frac{1}{T} \int_0^T \left[a(t_i) - a_{ave} \right]^2 dt \qquad (11)$$

This can be expanded by using the concept of generalised arithmetical operations such as: $(a-b)^2 = a^2-2ab+b^2$ and derive it with respect to time. Consequently, the acceleration noise can be expressed as follows (Drew 1968):

$$(\sigma_a)^2 = \frac{1}{T}\int_0^T \left[a(t_i)\right]^2 dt - (a_{ave})^2 \qquad (12)$$

It might be supposed that if a motorist is able to operate a vehicle on a perfect roadway without the influence of other traffic, the acceleration noise would be zero or near to zero. In this study the acceleration noises were calculated from the speed data measured with the instrumented vehicle. The relationship between acceleration noise and running speed on Hämeenlinnanväylä when the test vehicle is following a heavy vehicle can be expressed as follows:

$$\sigma_a = 9.8 - 0.216\,v + 0.0012\,v^2 \qquad R^2 = 0.33 \qquad (13)$$

where v (km/h) is speed and σ_a (m/s^2) is acceleration noise of the test vehicle.

Equation (13) was calibrated by pooling the data from all measurements. Standard regression technique was employed to test the relationship between acceleration noise and running speed expressed in *Equation (13).* The data used for developing the polynomial model were the average of 10 seconds data.

The acceleration noise of the test vehicle when following a heavy vehicle on Hämeenlinnanväylä fluctuated between 0.1 m/s^2 and 0.71 m/s^2. Minimum acceleration noise occurs at speeds between 80 to 90 km/h. The acceleration noise as a function of speed is shown in *Figure 7.*

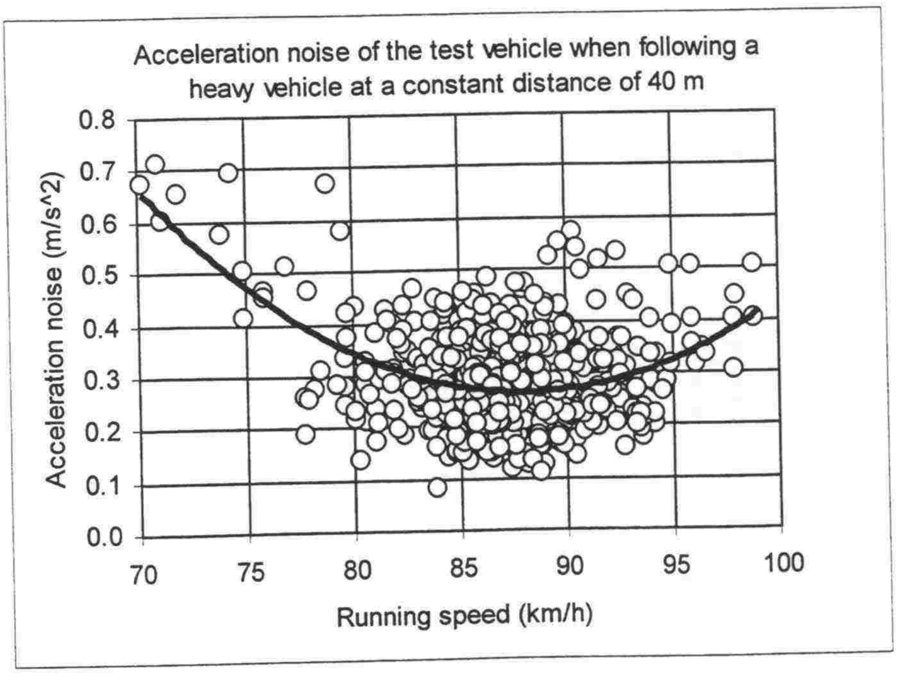

Figure 7. Relationship between acceleration noise and speed on Hämeenlinnanväylä when the test vehicle is following a heavy vehicle.

5 GAP AND SPEED DIFFERENCE

5.1 General

The gap between the vehicles is the distance between the back bumper of the leader and the front bumper of the follower. This gap can be described in terms of spatial or temporal distance (i.e. in meter or in seconds). Gap was used instead of headways, because it was assumed that the vehicle lengths have little effect on the following behavior of the drivers. Speed difference is the difference between the speeds of the leading vehicle and the following vehicle.

Gap is one of the most important parameters for simulation models. In reality a free driver is not influenced by other traffic and can drive with his desired speed. A following driver, however, has to adjust his driving at least for some time, to the driver in front of him. The gap between two moving vehicles in a constrained traffic stream is different from that in an unconstrained traffic stream. In a constrained traffic stream each individual driver must adjust his behaviour to the behaviour of the other drivers as well as to the gap to the preceding vehicle (Parker 1996).

5.2 Car following gap

Two classes of gaps were estimated in this study using data, which were measured using the instrumented light vehicle with test drivers. The speed limit of the investigated road section was 120 km/h and the length about 30 km. About 200 observations were analysed and sorted into two different classes: gap before overtaking a heavy vehicle and gap after overtaking a heavy vehicle. Gap before overtaking is the gap to the heavy vehicle in front and gap after overtaking is the gap to the heavy vehicle behind. The gap (in seconds) between the test vehicle and the heavy vehicle was calculated using the equations given below:

$$G_{before} = \frac{d_1}{V_t} = \frac{(T_1 - T_0)d_1}{S_t} \tag{14}$$

$$G_{after} = \frac{d_2}{V_h} = \frac{d_2(T_1 - T_0)}{d_1 + S_t - d_0} \tag{15}$$

where:

G	= gap between two vehicles (seconds)
T_0	= initial time (s)
T_1	= time when travelled a certain distance (s)
S_t	= travelled distance by test vehicle in time interval T1-T0 (m)
S_h	= travelled distance by heavy vehicle in time interval T1-T0 (m)
V_t	= speed of the test vehicle (km/h)
V_h	= speed of the heavy vehicle (km/h)
d_0	= initial distance between test vehicle and heavy vehicle (m)
d_1	= distance between test vehicle and heavy vehicle (m)
d_2	= distance between heavy vehicle and test vehicle (m)

The symbols of *Equations 14-15* are given in *Figure 8*. Distances between test vehicle and heavy vehicle and speed of the test vehicle were available in the data set. Distances between heavy vehicle and light vehicle (d_2), and speed of the heavy vehicle (V_h) were estimated using the space-time diagram given below.

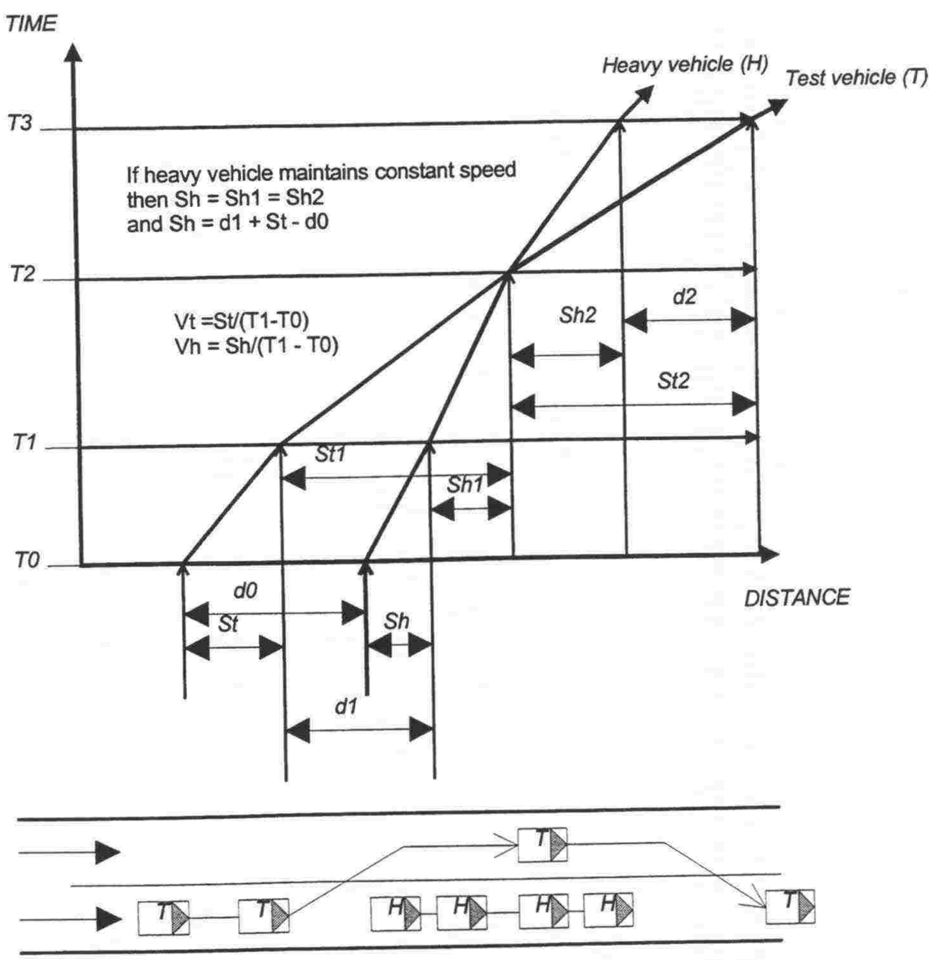

Figure 8. Space-time diagram for overtaking maneuvers.

The gap just before changing lane for overtaking varied between 0.8 s and 3.6 s. After completion of the overtaking maneuver the gap to the heavy vehicle behind varied between 0.3 s and 4.8 s. *Table 9* presents the minimum and maximum values of the gap distribution.

Table 9. Gap (s) and speed difference (m/s) between the test vehicle and heavy vehicle based on moving observation car measurements.

Parameter	Min	Max	Mean	Median	Standard deviation	95% confidence interval	Number of observations
Speed difference Before overtaking	0.4	13.6	5.8	6.1	2.9	5.8±0.66	77
Speed difference After overtaking	1.9	17.1	7.4	7.2	2.6	7.4±0.48	77
Gap Before overtaking	0.8	3.6	1.9	1.8	0.6	1.9±0.14	116
Gap After overtaking	0.3	4.8	1.4	1.2	0.8	1.4±0.15	116

According to the calculations, the gap between two vehicles increases as the speed differences between the vehicles increase (*Figure 9*). About 58% of the gaps were between 1 and 2 seconds just before overtaking the heavy vehicle and almost 50% of the gaps were between 1 and 2 seconds just after completion of the overtaking maneuver. The frequency and the cumulative distribution of gaps between the test vehicle and the heavy vehicle just before and just after overtaking are given in *Figure 10*.

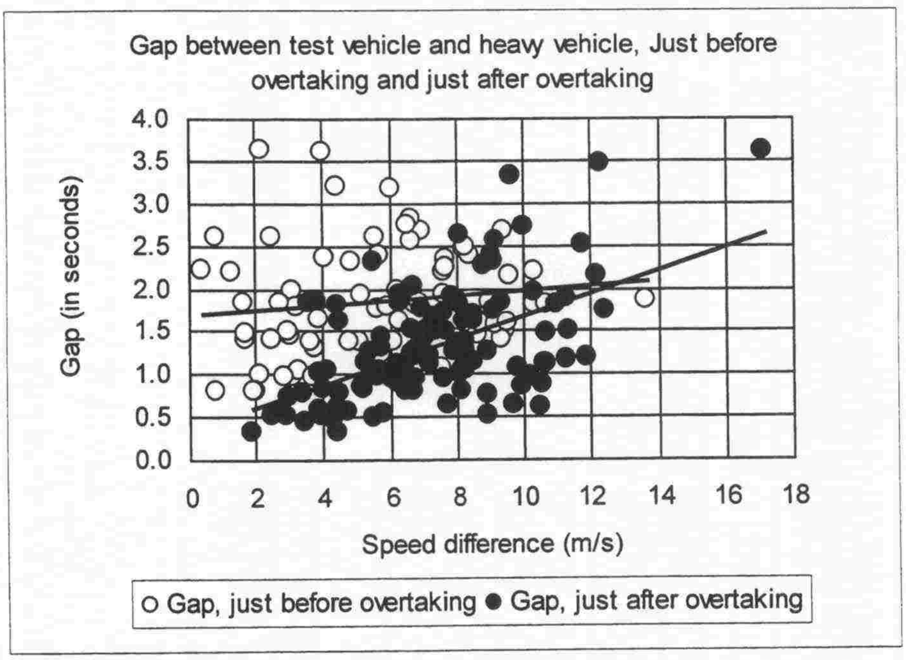

Figure 9. Gap and speed difference between test vehicle and heavy vehicle.

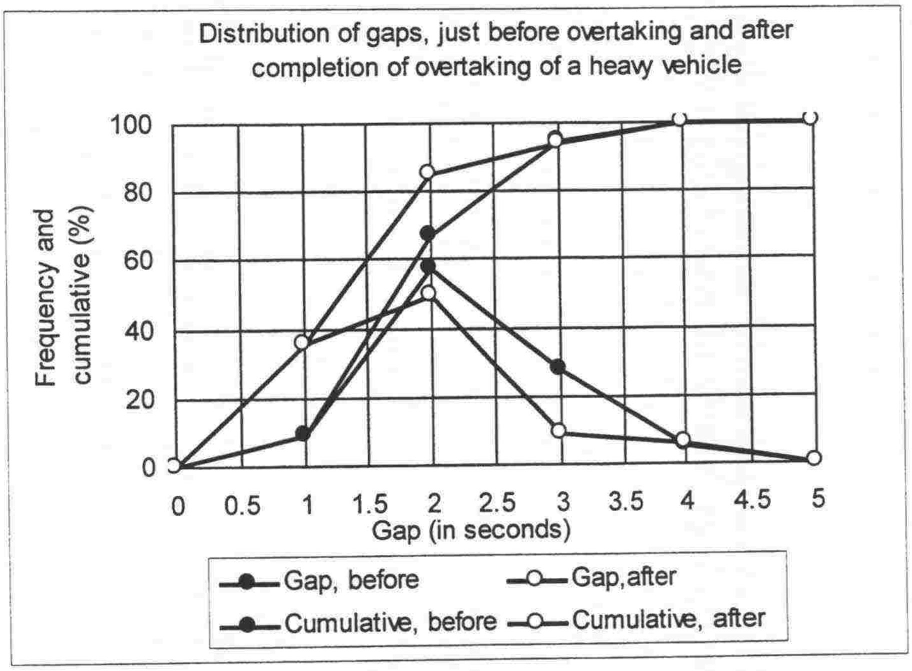

Figure 10. The frequency of the gap distribution between light vehicle and heavy vehicle based on car moving observation measurements.

5.3 Gap and vehicle type

Gap describes the distance between successive vehicles occupying the same lane. This is directly related to the perception-reaction time of the following driver in response to changes in the speed of the leading vehicle. On the other hand, this distance can be related to the types of the leading and following vehicles in the traffic stream. Consequently, the gap between two vehicles also depends on the traffic states (i.e. congested or non-congested).

For analysing gaps for different vehicle types three flow states were considered. The 15th percentile, 50th percentile and 85th percentile gaps for each flow state namely 584, 823 and 1,228 veh/h were calculated. Gap distributions were gleaned from the data files for four vehicle following combinations, i.e. the gaps when a light vehicle follows a light vehicle (LL), a heavy vehicle follows a heavy vehicle (HH), a light vehicle follows a heavy vehicle (LH), and a heavy vehicle follows a light vehicle (HL). The gaps were calculated from the point measurement data (LAM 128 on Ring Road III) of the basic lane, only. This is because the passing lane carries almost only passenger cars. The speed limit was 80 km/h on the road section in question.

The mean gap size was always smaller for a light vehicle following a heavy vehicle than for the other three combinations. No other clear differences were found. The mean gap size, when a heavy vehicle follows a light vehicle is sometimes larger than for other vehicle combinations and sometimes smaller.

Table 10. Gaps for different following situations on Ring Road III.

Following type	15th percentile gap (s)	50th percentile gap (s)	85th percentile gap (s)	Mean gap (s)	Flow rate (veh/h/lane)
LL	1.3	3.5	9.2	5.4	584
HL	2.3	3.3	15.5	7.7	
HH	2.1	2.8	12.9	6.5	
LH	1.2	3.5	6.9	5.8	
LL	1.2	2.8	7.7	4.2	823
HL	1.2	3.4	6.4	3.8	
HH	1.4	2.3	4.2	2.6	
LH	1.1	2.3	3.9	2.6	
LL	1.0	2.1	4.1	2.6	1,228
HL	1.4	2.7	5.1	3.2	
HH	1.7	2.5	3.1	2.4	
LH	0.9	1.8	3.0	2.2	

According to the analyses a heavy vehicle followed a light vehicle at a larger gap than a heavy vehicle followed a heavy vehicle. One example of the cumulative distributions of gaps for different vehicle combinations is illustrated in *Figure 11*. For flow rate 1,228 veh/h the mode of gap was between 2 and 3 seconds when heavy vehicle followed heavy vehicle. The modes of gap were between 1 and 2 seconds for the other three combinations. Usually the speed differences between light vehicles and heavy vehicles were smaller at high flow rates than at low flow rates. Therefore, the gaps between light vehicles and heavy vehicles were smaller at high flow rates than at low ones.

There is a variation in gap distributions based on speed limit. On freeway cross sections where speed limit was 80 km/h the mode of gap was between 1 and 2 seconds for both lanes. On sections where speed limit was 100 km/h the mode of gap was between 1 and 2 seconds on basic lanes and around 1 second on passing lanes. The mode of gap was also around 1 second on passing lane where speed limit was 120 km/h. There was a peak between 1 and 2 seconds and frequencies stayed high up to around 14 seconds on basic lanes when speed limit was 120 km/h. Mean gaps and standard deviation of speeds were higher in high speed limit areas than in low speed limit areas. The gap distributions at different speed limit areas are shown in *Figures 11-14.*

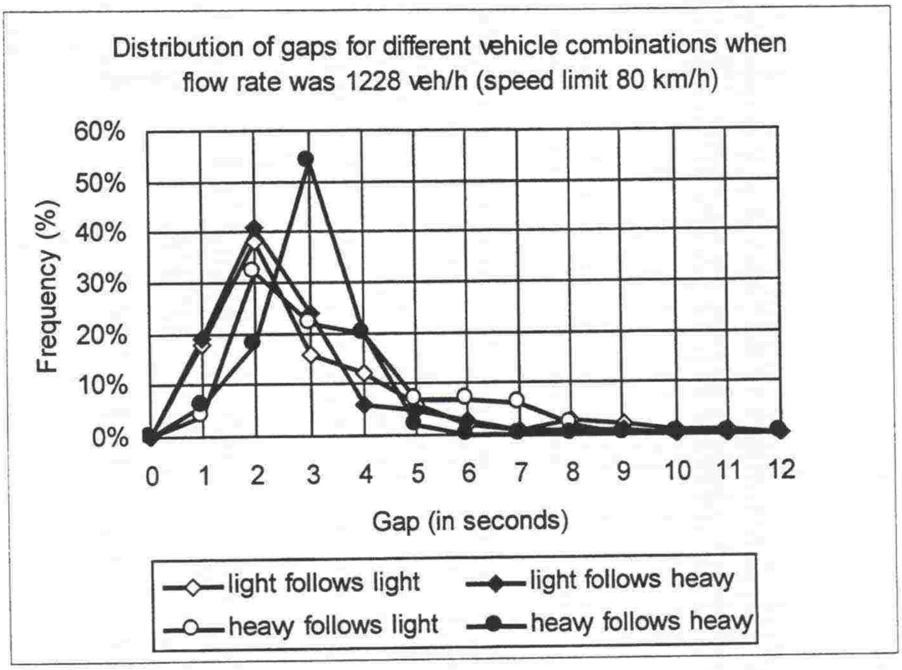

Figure 11. Distribution of gaps for different vehicle combinations for a 15-minute count on Ring Road III.

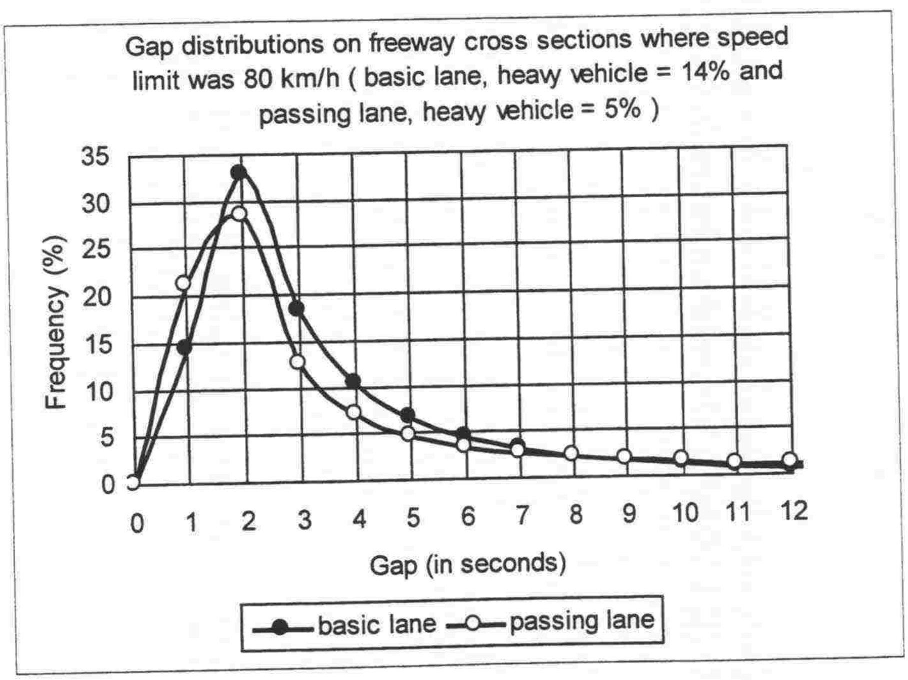

Figure 12. Gap distributions on freeway cross sections where speed limit was 80 km/h (basic lane N = 80,278, Mean gap = 3.6, σ = 4.6 and passing lane N = 60,627, Mean gap = 6.0, σ = 12.8).

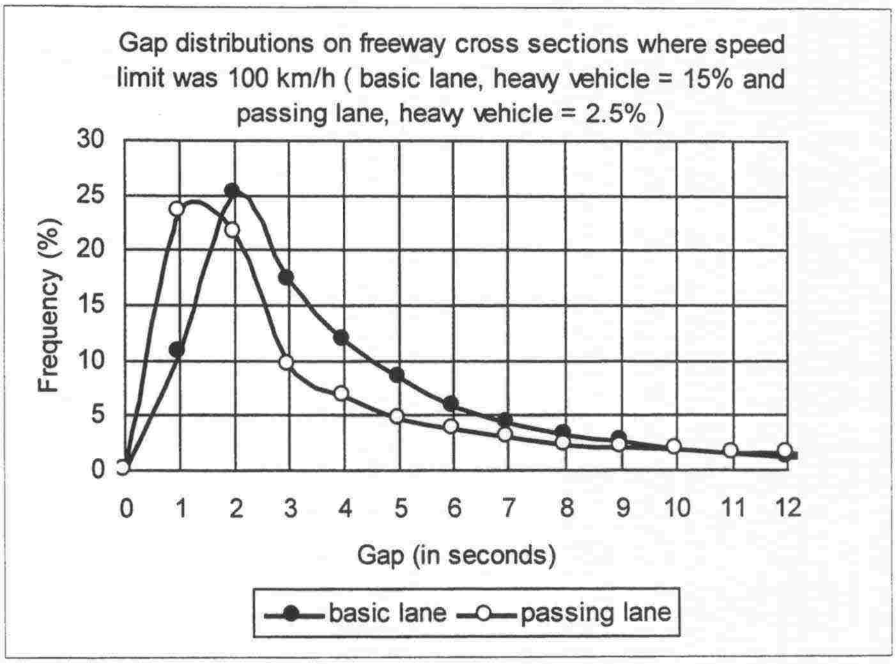

Figure 13. Gap distributions on freeway cross sections where speed limit was 100 km/h (basic lane N = 75,240, Mean gap = 4.4, σ = 5.0 and passing lane N = 34,525, Mean gap = 9.3, σ = 20.2).

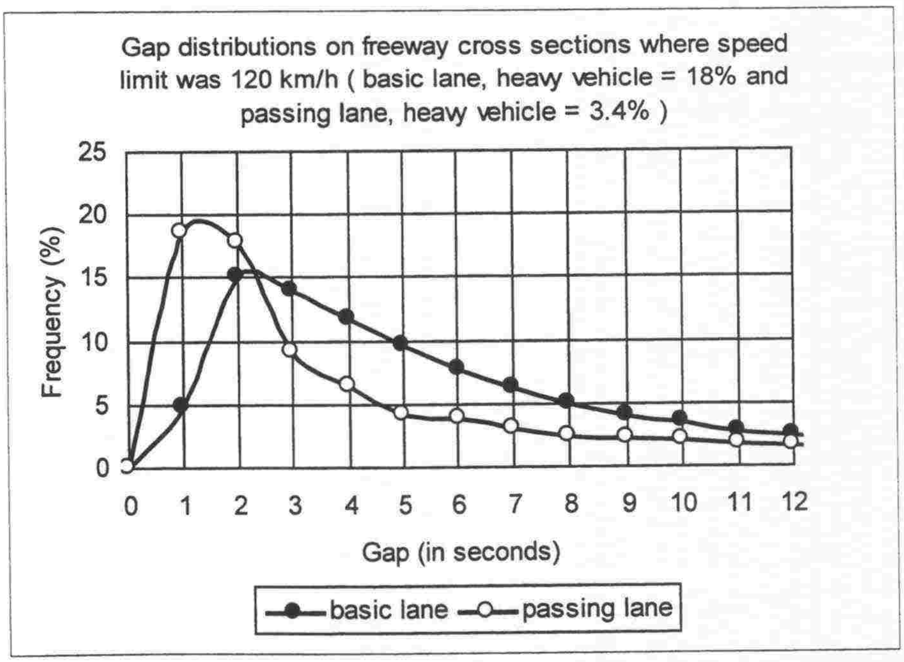

Figure 14. Gap distributions on freeway cross sections where speed limit was 120 km/h (basic lane N = 33,717, Mean gap = 6.5, σ = 6.5 and passing lane N = 13,112, Mean gap = 14.4, σ = 28.1).

6 SPEED BASED ON CAR FOLLOWING

6.1 Speeds of the heavy vehicles on the Keimola - Hyvinkää section

The instrumented vehicle was used to measure the speed level as described earlier. The investigated road section was between Keimola and Hyvinkää on Hämeenlinnanväylä (about 30 km). The speed limit on the road section was 120 km/h. The average running speed when following a heavy vehicle at a constant distance of about 40 m towards Keimola fluctuated between 87 km/h and 88 km/h. The standard deviation of running speeds varied between 2.1 and 2.4 km/h. The 85th percentile running speed was under 100 km/h and 15th percentile running speed was under 85 km/h. These speed characteristics on Hämeenlinnanväylä are illustrated in *Table 11*.

Table 11. Running speeds at Hämeenlinnanväylä, when the test vehicle followed a heavy vehicle at a constant distance of about 40 m.

Direction	Type of leading vehicle	Average running speed (km/h)	V 85% (km/h)	V 15% (km/h)	σ_v (km/h)
Keimola-Hyvinkää	Truck with trailer	91	96	85	3.0
Keimola-Hyvinkää	Truck with trailer	84	88	82	3.1
Keimola-Hyvinkää	Truck with trailer	86	88	86	1.6
Hyvinkää-Keimola	Truck	88	94	83	2.2
Hyvinkää-Keimola	Truck with trailer	87	93	81	2.1
Hyvinkää-Keimola	Truck with trailer	87	88	82	2.4

The average running speed towards Hyvinkää fluctuated between 84 km/h and 91 km/h. The 85th percentile running speed was also under 100 km/h. The 15th percentile running speeds fluctuated between 82 km/h and 86 km/h. The standard deviation of running speeds varied between 1.6 and 3.1 km/h. Some smaller and irregular fluctuations with higher amplitudes were observed when following the heavy vehicles in each direction, probably due to geometrical factors. The speed profiles when the test vehicle followed a heavy vehicle at a constant distance attempting to keep the same speed as the leading heavy vehicle are illustrated in *Figure 15* and *Figure 16*.

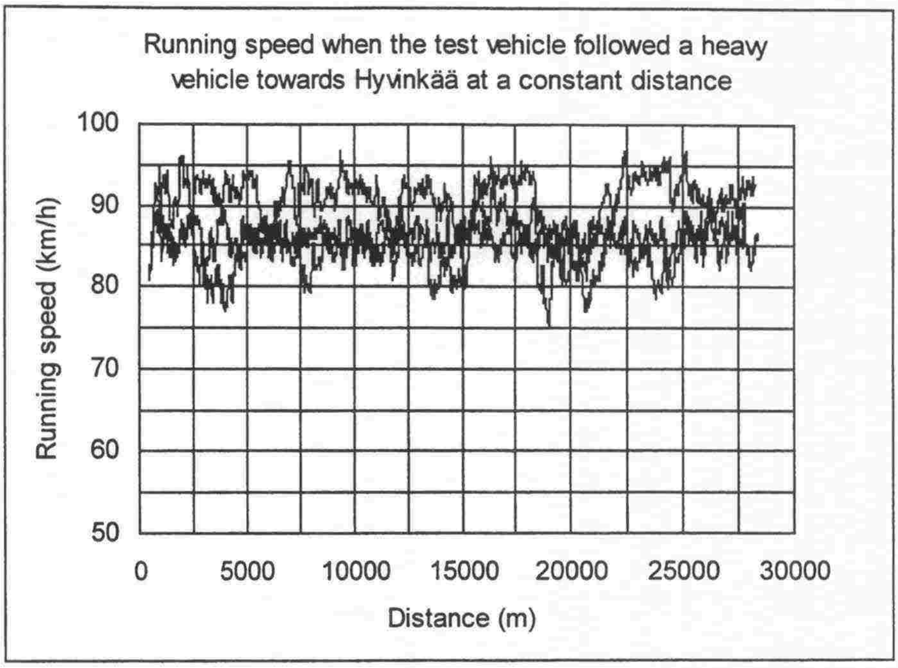

Figure 15. Running speeds towards Hyvinkää when the test vehicle followed a heavy vehicle at a constant distance (40 m).

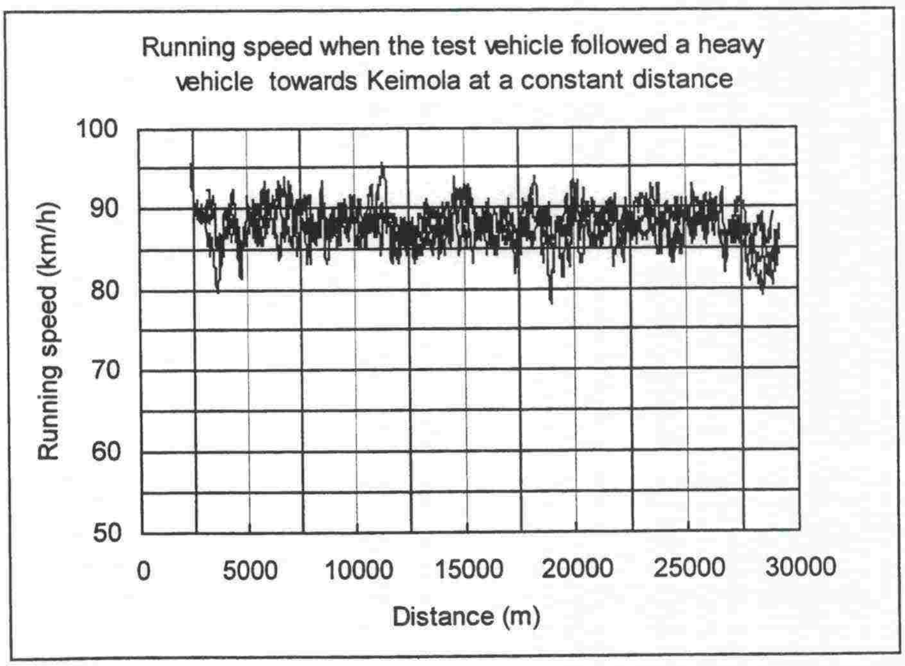

Figure 16. Running speeds towards Keimola when the test vehicle followed a heavy vehicle at a constant distance (40 m).

6.2 Speed level on Ring Road III

The investigated road section was Ring III between Isontammentie and Vanha Porvoontie. Ring Road III was chosen as a measurement location because it was acting as a test site for another part of the project and will be rebuilt to freeway standard in the future. One of the purposes with the new simulation tool will be to simulate the effects of the road work arrangements. The length of the road section was about 14 km. Speed data were collected using the instrumented vehicle as described earlier. The instrumented vehicle was driven five times back and forth through the traffic stream on a Monday from 9.45 to13.15. The investigation section was divided into 7 subsections for calculating average running speeds. The speed characteristics were calculated for each subsection. Some data were deleted to avoid the influence of the traffic lights, because the main aim of the study was to find out the speed levels in freeway conditions. On the other hand the 85th percentile and 15th percentile running speeds were calculated without deleting any data points. Average, 85th percentile and 15th percentile speeds for each subsection were calculated by pooling the data set from all measurements. The speed limit of the road section was 80 km/h.

The average, 15th percentile and 85th percentile running speeds on different subsections are shown in *Tables 12-13*. The speed profiles throughout the investigated sections are shown in *Figures 17-18*. There were some differences in the running speeds between the measurement periods. Towards east the 85th percentile running speed varied between 73 and 89 km/h, the 15th percentile running speed between 48 and 74 km/h, and the average running speed between 63 and 83 km/h. The average running speed was quite low on the section between Isontammentie and Hämeenlinnanväylä towards east. Very high average running speed was observed on the section between Tikkuritie and Vanha Porvoontie. The standard deviation of running speeds varied between 5.8 and 14.2 km/h.

Towards west the average running speed varied between 70 and 82 km/h. The 85th percentile running speed was below 90 km/h and the 15th percentile running speed was below 80 km/h. The 85th percentile running speed varied between 79 and 88 km/h and 15th percentile running speed varied between 20 and 72 km/h. The average running speed was quite low on the section between Suutarilantie and Tuusulantie and quite high on the section between Vanha Porvoontie and Tikkuritie. The standard deviation of speed varied between 4.4 and 9.4 km/h. Higher standard deviations of speed were found on some subsections, probably due to influence of traffic lights.

Table 12. Running speeds towards east (towards Vanha Porvoontie) on Ring Road III when test vehicle was driven in the traffic stream.

Subsections All measurements	Distances (m)	$V_{15\%}$ (km/h)	$V_{85\%}$ (km/h)	Average (km/h)	σ_V (km/h)	Number of observations
Isontammentie-Hämenlinnanväylä	460	50	73	63	8.1	132
Hämeenlinnanväylä-Tuupakantie	2080	64	82	75	6.2	504
Tuupakantie-Lentoasemantie	3810	58	87	77	12.1	966
Lentoasemantie-Tuusulanväylä	1380	48	88	76	14.2	372
Tuusulanväylä-Suutarilantie	1960	52	78	69	7.6	553
Suutarilantie-Tikkuritie	840	62	86	74	9.8	218
Tikkuritie-Vanha Porvoontie	2870	74	89	83	5.8	640

Table 13. Running speeds towards west (towards Isontammentie) on Ring Road III when test vehicle was driven in the traffic stream.

Subsections All measurements	Distances (m)	$V_{15\%}$ (km/h)	$V_{85\%}$ (km/h)	Average (km/h)	σ_V (km/h)	Number of observations
Vanha Porvoontie-Tikkuritie	2860	70	88	82	7.5	649
Tikkuritie-Suutarilantie	820	52	82	74	7.4	223
Suutarilantie-Tuusulanväylä	1880	20	79	70	9.4	588
Tuusulanväylä-Lentoasemantie	1480	72	87	80	4.4	335
Lentoasemantie-Tuupakantie	3810	62	86	76	8.0	946
Tuupakantie-Hämeenlinnanväylä	2080	68	85	77	7.8	490
Hämeenlinnanväylä-Isontammentie	450	30	79	72	7.8	130

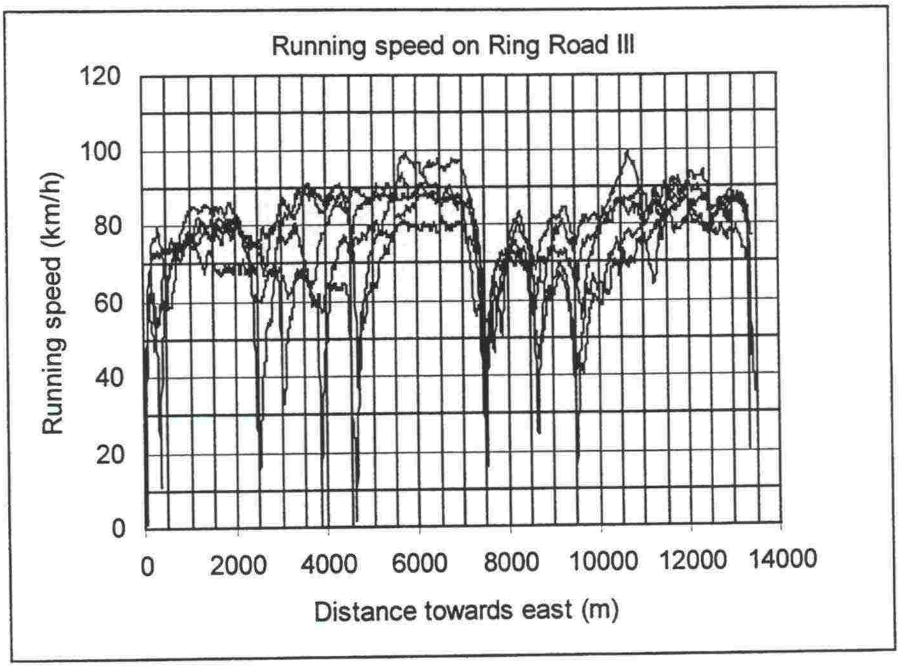

Figure 17. Running speeds towards east (towards Vanha Porvoontie) on Ring Road III during different measurement periods when test vehicle was driven in the traffic stream.

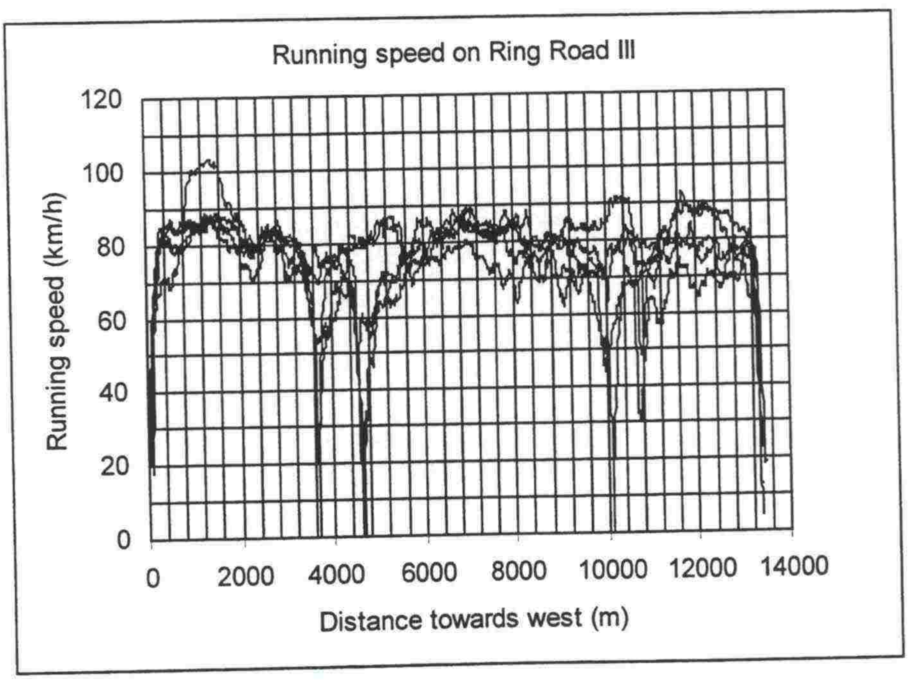

Figure 18. Running speed towards west (towards Isontammentie) on Ring Road III during different measurement periods when test vehicle was driven in the traffic stream.

7 TRAVEL SPEED AND FLOW RATE

7.1 General

The main aim of the travel speed study was to gather information about the travel speed of different vehicle types on different types of entrance ramps, upgrades and downgrades, and on level sections. The data were collected using successive video cameras with a timer of 1/10th of a second. A total of 25.5 hours of videotapes was recorded from which data on traffic volume, vehicle classification, and travel speeds were obtained. The vehicles were grouped into six vehicle types. Passenger cars, minibuses, vans, and motorcycles were grouped into type 1. Buses were grouped into type 2. Passenger cars and vans with trailer were grouped into type 3. Light trucks were grouped into type 4, semi-trailer combination trucks were grouped into type 5 and full trailer combination trucks were grouped into type 6. Vehicle type 1 was considered as light vehicles and vehicle types 2 to 6 as heavy vehicles.

7.2 Travel speed on a level freeway section

Data were collected using two video cameras, which were positioned on Turunväylä from 14:30 PM to 17:30 PM on a Friday afternoon in August. The distance between the cameras was 6,513 m and the speed limit was 100 km/h. The data included information of 4,358 vehicles from which the travel speed and flow rate were calculated. The 5-minute flow rates varied between 1,336 and 1,924 veh/h (both lanes together). The proportion of heavy vehicles fluctuated between 8.1 and 18.3%.

The 85th percentile travel speed was below 120 km/h. The 15th percentile speed was about 75 km/h. The speed difference between light vehicles and heavy vehicles usually varied between 0 and 16 km/h. The cumulative distributions of speeds for each vehicle type are presented in *Figures 19-20*. The overall speeds of the light vehicles on this section fluctuated between 75 and 120 km/h and of the heavy vehicles between 60 and 102 km/h. The relationship between average travel speed and one-way flow rate has been established using linear regression. The parameters of the regression models are given in *Table 14*. The mode of the speeds of the light vehicles was about 105 km/h and for the heavy vehicles it was about 85 km/h (*Appendix C*).

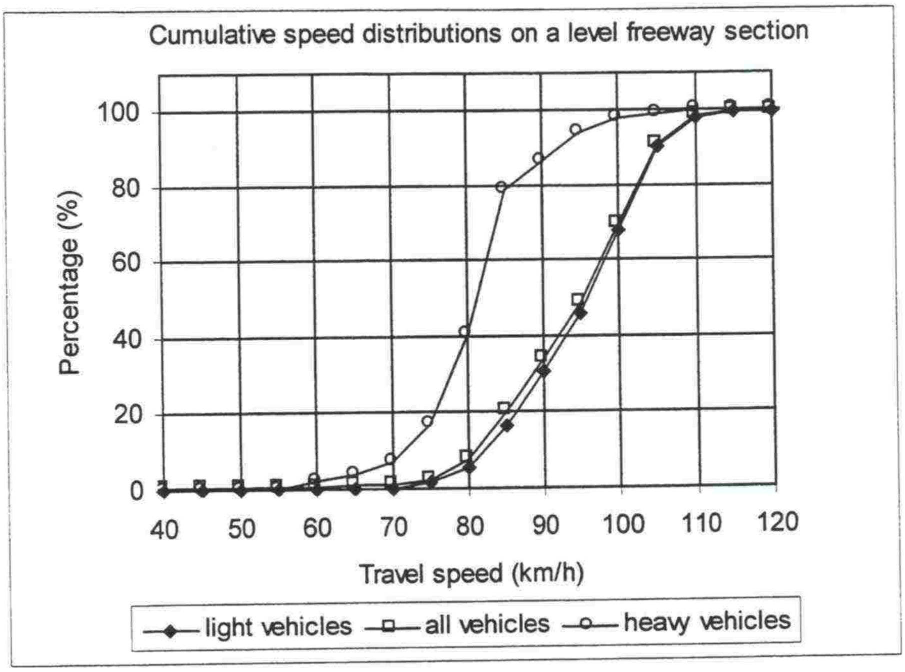

Figure 19. Cumulative distributions of speeds on a level freeway section towards Turku on Turunväylä.

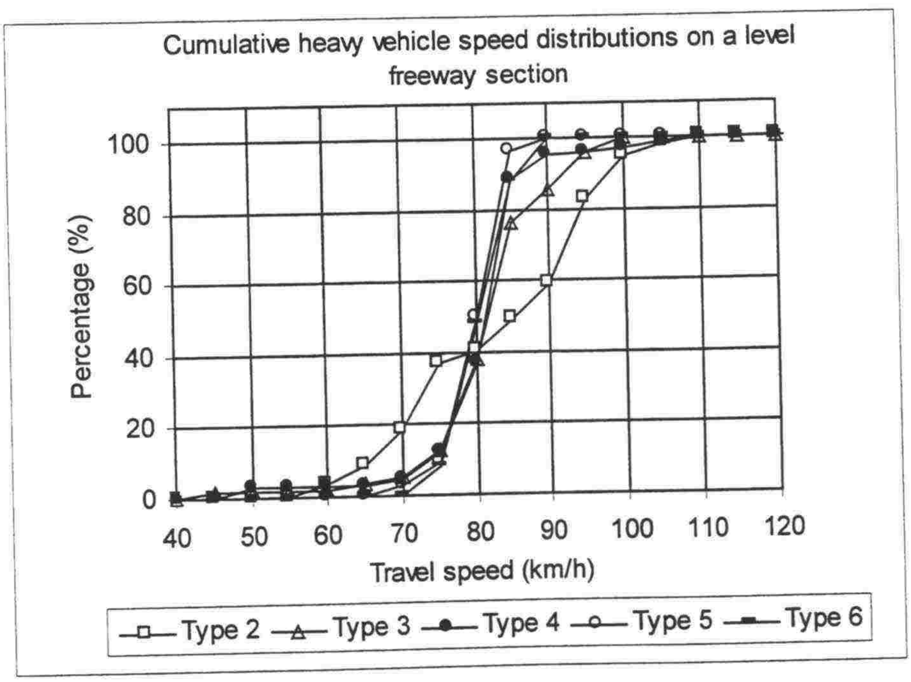

Figure 20. Cumulative heavy vehicle speed distributions on a level freeway section towards Turku on Turunväylä. The vehicle type numbers refer to section 7.1.

Table 14. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on a level freeway section. ***Model:*** $\boldsymbol{V = a + b \times q}$ *(q_{range} = 1,336-1,924 veh/h)*

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.0003	93.58	0.01
$V_{15\%}$	-0.0017	88.91	0.04
$V_{85\%}$	-0.0075	118.17	0.63
V_{light}	-0.0043	101.61	0.17
V_{heavy}	-0.0058	95.53	0.05

With linear regression the relationship between average travel speed V (km/h), flow rate Q (veh/h), and share of heavy vehicles (HV%) has been established. This relationship is shown in *Equation (16)*. Based on the model, average travel speeds decrease as flow rate and proportion of heavy vehicle increase in traffic stream. Travel speeds as a function of flow rate for different proportion of heavy vehicles are illustrated in *Figure 21*.

$$V_{average} = 113.63 - 0.0075\,Q - 0.616\,(HV\%) \qquad R^2 = 0.27 \qquad (16)$$

The average speed difference between light and heavy vehicles was estimated using a dummy variable and the result is given in *Equation (17)*. Based on estimation the average speed of the light vehicles was almost 9 km/h higher than that of heavy vehicles.

$$V_{average} = 102.93 - 0.0051\,Q - 8.72\,D \qquad R^2 = 0.66 \qquad (17)$$

where D = 0 for light vehicles and 1 for heavy vehicles.

The intercepts of the models were statistically significant and P-values were less than 0.00001. The coefficients of Q were not statistically significant for both models.

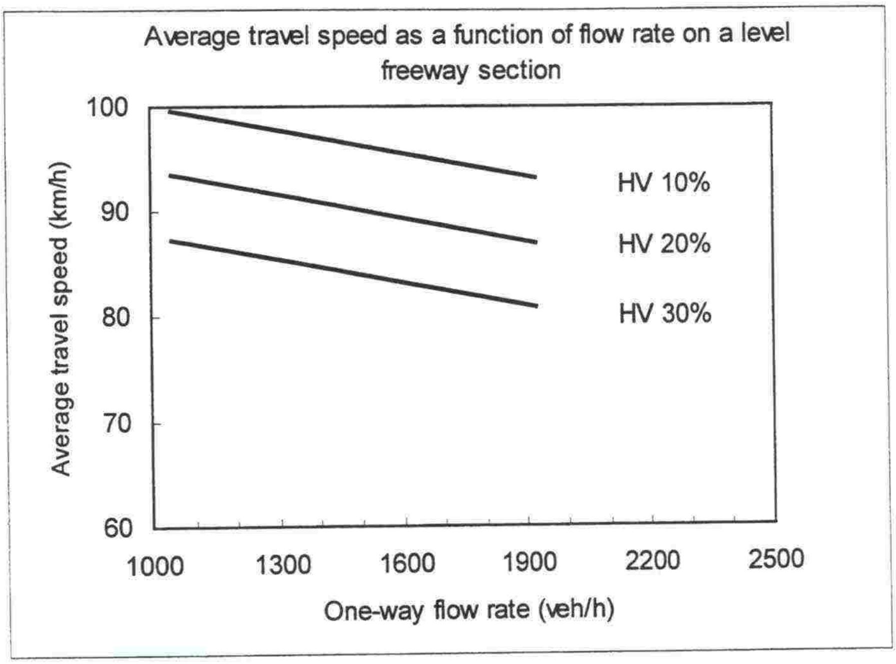

Figure 21. Average travel speed as a function of flow rate for different shares of heavy vehicles on a level freeway section on Turunväylä. The speed lines are drawn using Equation (16).

7.3 Travel speed on entrance ramps

7.3.1 Travel speed on the ramp from Ring Road I to Turunväylä

The curve radius of the downgrade loop ramp from Ring Road I to Turunväylä varies between 60 and 100 m. The grade is 2.8% and the configuration of the ramp is given in *Appendix D*. The speed limit is 70 km/h. A total of 3 hours of videotapes were recorded with 2 cameras including information of 1,012 (959 light and 53 heavy) vehicles from which the travel speeds and flow rates were calculated. The distance between the video cameras was 268 m. The 5-minute rate of heavy vehicles varied from 2 to 14%.

The speed difference between light and heavy vehicles varied between 0 and 12 km/h. The cumulative speed distributions of different vehicle types are illustrated in *Figures 22-23*. The speed of the heavy vehicles fluctuated between 15 and 49 km/h and the speed of the light vehicles between 25 and 55 km/h. The mode of the speeds for light vehicles was about 32 km/h and for heavy vehicles about 45 km/h (*Appendix C*).

The relationship between travel speed and one way flow rate was established with linear regression. The parameters of the regression models are given in *Table 15.* The R^2 values of the models are small, which means that the relationship between flow rate and speed on ramp was very weak. On the other hand, one reason for that was the small flow range (208-452 veh/h) on the ramp. According to the analyses, the travel speed on the ramp was much lower than the posted speed. The 85th percentile speed on the ramp was only 4.5 km/h higher than the average travel speed. The mean travel speed on the ramp was 45.5 km/h and the standard deviation was 5.1 km/h for the whole data set. The average travel speed of heavy vehicles on the ramp was about 7-8 km/h lower than the speed of light vehicles. The slope of the regression line was steeper for heavy vehicles than for light vehicles.

Table 15. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on the ramp from Ring Road I to Turunväylä towards west. ***Model: V = a + b x q***
(q_{range} = 208-452 veh/h)

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.0021	45.70	0.03
$V_{15\%}$	-0.0024	41.58	0.01
$V_{85\%}$	-0.0014	50.17	0.02
V_{light}	-0.0032	46.58	0.10
V_{heavy}	-0.0200	44.44	0.30

The relationship between average travel speed V (km/h), flow rate Q (veh/h), and HV% has been established using linear regression analysis. The regression equation is given below:

$$V_{average} = 47.61 - 0.0047\,Q - 0.175\,(HV\%) \qquad R^2 = 0.28 \qquad (18)$$

Based on *Equation (18),* it is obvious that the average travel speed decreases as the flow rate and HV% increase. However, the R^2 value increased significantly when HV% was included in the analysis. The intercept and the coefficient for the heavy vehicles in the model above are statistically significant and the value of P is less than 0.00001 (P<0.00001).

The average speed difference between light and heavy vehicles was also estimated using linear regression. A dummy variable was used in the model. The regression model is given below:

$$V_{average} = 49.58 - 0.0114\,Q - 8.14\,D \qquad R^2 = 0.82 \qquad (19)$$

where D = 0 for light vehicles and 1 for heavy vehicles.

According to the model light vehicles maintained 8 km/h higher speed than heavy vehicles. The intercept and the coefficient of the model are statistically significant at the level of 0.00001.

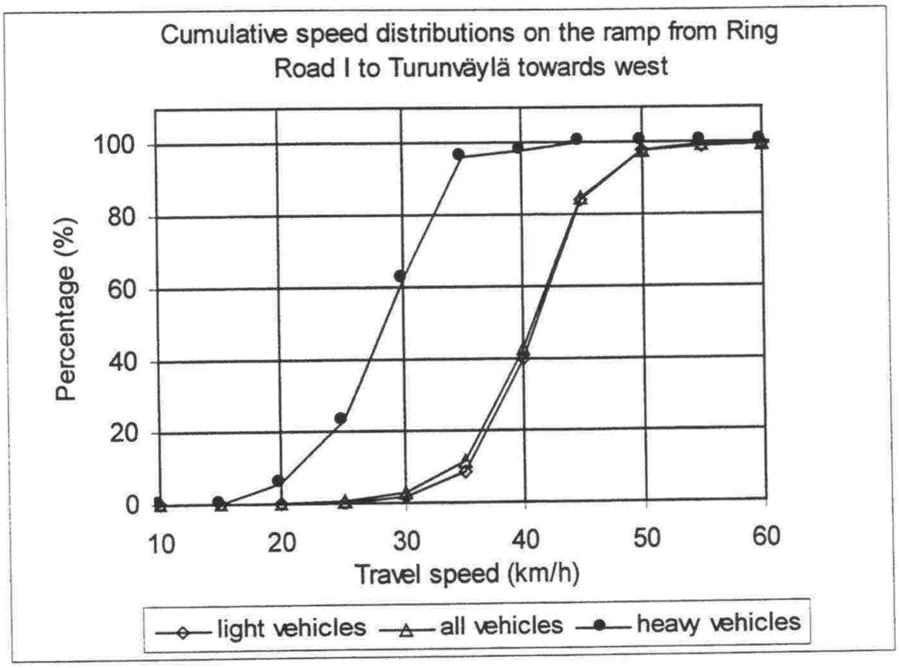

Figure 22. Cumulative speed distributions on the ramp from Ring Road I to Turunväylä towards west.

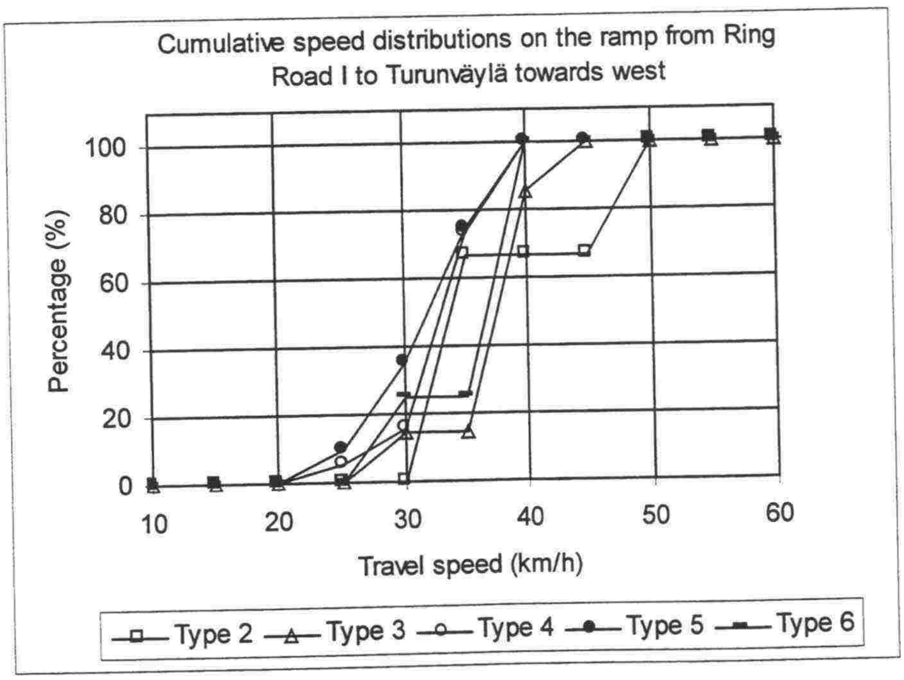

Figure 23. Cumulative distributions of travel speeds on the ramp from Ring Road I to Turunväylä towards west. The vehicle type numbers refer to section 7.1.

7.3.2 Travel speed on the ramp from Ring Road I to Lahdenväylä

The grade of the downgrade jug-handle ramp from Ring Road I to Lahdenväylä is 2.1%. The radius of the curve varies between 150 m and 300 m. The speed limit is 80 km/h. The configuration of the ramp is given in *Appendix D*. A total of 1.5 hours of videotapes were used from which the registration numbers of 558 (448 light and 110 heavy) vehicles were obtained. The 5-minute flow rate had an average of 394 veh/h. The distance between the two cameras was 810 m. The 5-minute rate of HV% had an average value of 20% and varied between 10% and 36%.

The speed of the heavy vehicles fluctuated between 50 and 85 km/h. The mode was around 70 km/h. The speed of the light vehicles fluctuated between 50 and 100 km/h. The mode was around 74 km/h (*Appendix C*). The speed difference between heavy and light vehicles usually varied between 0 and 5 km/h. The cumulative speed distributions of different vehicle types are illustrated in *Figures 24-25*.

The relationship between average travel speed, 85th percentile speed, 15th percentile speed, speed of the heavy vehicles, and speed of the light vehicles and traffic flow are shown using linear regression equations (*Table 16*). According to the analyses the speeds of the vehicles decreased as the flow rate increased. However, as for all the other ramps in this study, the R^2 values are very small and the flow range on the ramps is very narrow.

Table 16. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on the ramp from Ring Road I to Lahdenväylä towards Lahti. ***Model: $V = a + b \times q$*** *(q_{range} = 312-457 veh/h)*

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.007	77.28	0.03
$V_{15\%}$	-0.021	75.44	0.09
$V_{85\%}$	-0.004	83.69	0.01
V_{light}	-0.012	80.31	0.08
V_{heavy}	-0.002	70.96	0.01

The 85th percentile speed of the heavy vehicles was 73.5 km/h, which was 5.5 km/h lower than that of the light vehicles. The 15th percentile speed of the heavy vehicles was around 58 km/h, which was 6 km/h lower than that of the light vehicles.

The relationship between average travel speed (km/h), flow rate (veh/h), and HV% was also established with linear regression (*Equation 20*). The intercept and the coefficient for the heavy vehicle are statistically significant at the level of 0.00001 but the coefficient for the flow rate is not statistically significant. However, it is obvious that the average speeds decrease as the flow rate and proportion of heavy vehicles increase.

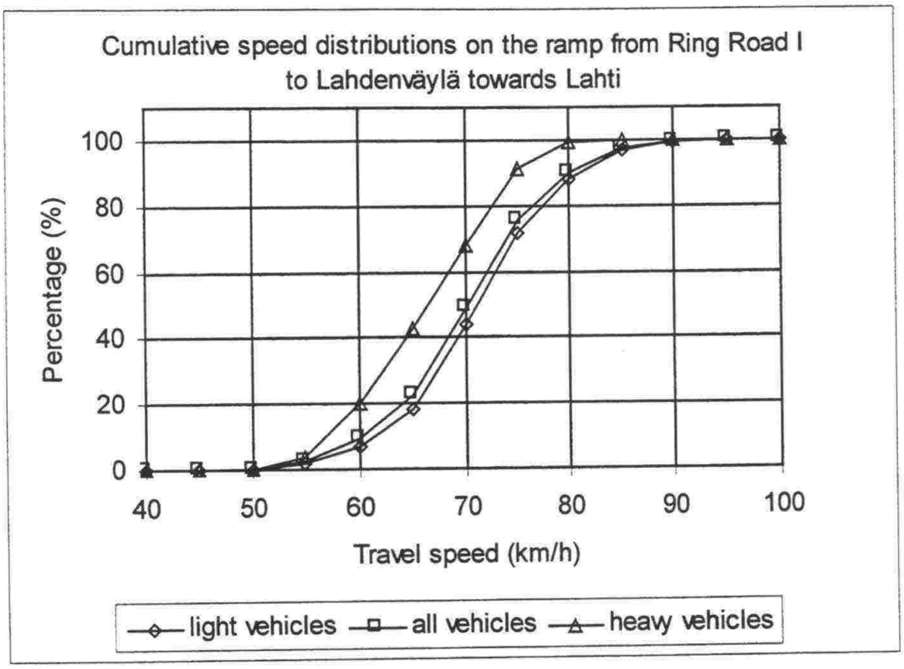

Figure 24. Cumulative speed distributions on the ramp from Ring Road I to Lahdenväylä towards Lahti.

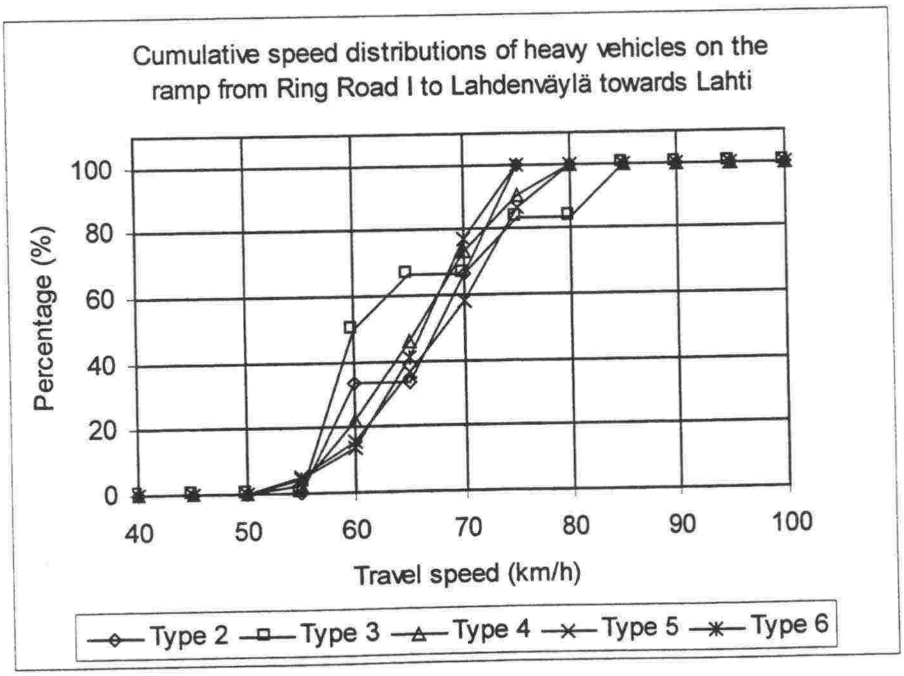

Figure 25. Cumulative speed distributions of heavy vehicles on the ramp from Ring Road I to Lahdenväylä towards Lahti. The vehicle type numbers refer to section 7.1.

$$V_{average} = 88.79 - 0.0218\ Q - 0.3077\ (HV\%) \qquad R^2 = 0.56 \qquad (20)$$

Average speed difference between light and heavy vehicles was estimated using linear regression with a dummy variable. The regression model is given below:

$$V_{average} = 78.22 - 0.0068\ Q - 5.18\ D \qquad R^2 = 0.49 \qquad (21)$$

where D = 0 for light vehicles and 1 for heavy vehicles.

The intercept and the coefficient of the dummy variable are statistically significant but the coefficient of the flow rate is not statistically significant. According to the model light vehicles maintained 5 km/h higher speed than heavy vehicles. Travel speeds as a function of flow rate for different proportion of heavy vehicles are illustrated in *Figure 26.*

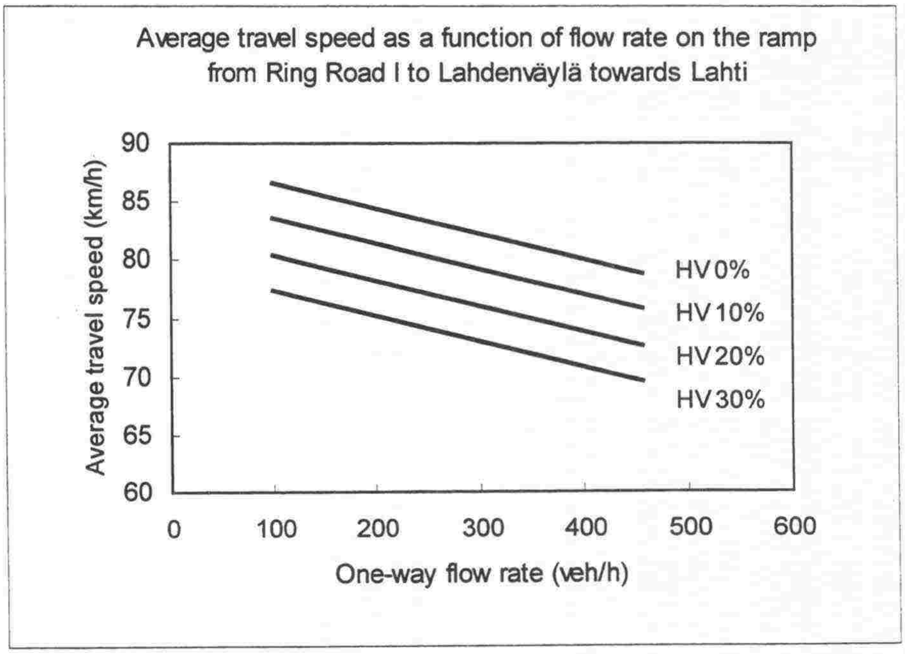

Figure 26. Average travel speed as a function of flow rate on the ramp from Ring Road I to Lahdenväylä towards Lahti. The speed lines are drawn using Equation (20).

7.3.3 Travel speed on the ramp from Ring Road III to Lahdenväylä

The grade of the jug-handle downgrade ramp from Ring Road III to Lahdenväylä is 1.7%. The speed limit is 70 km/h. The radius of the curve varies between 128 m and 200 m and the configuration of the ramp is given in *Appendix D.* Two video cameras were used for collecting data. The distance between the two cameras was 620 m. A total of 1.5 hours of videotapes was recorded, which produced information of 503 (445 light and 58 heavy) vehicles. The average flow rate was 340 veh/h. The 5-minute rate of the proportion of heavy vehicles had an average value of 12%, and varied between 5 and 30%.

The travel speeds of the heavy vehicles fluctuated between 40 and 85 km/h. The mode was around 65 km/h. The speed of the light vehicles fluctuated between 40 and 95 km/h. The mode was around 69 km/h (*Appendix C*). The 85th percentile speed for heavy vehicles was 65 km/h and for light vehicles 74.5 km/h. The 15th percentile speed for heavy vehicles was 50.5 km/h and for light vehicles 59 km/h. The speed differences between heavy and light vehicles varied between 0 and 7 km/h. The cumulative distributions of speeds for each vehicle type are presented in *Figures 27 and 28.* The same calculations were made as for the other ramps (*Table 17, Equations 22-23*).

Table 17. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on the ramp from Ring Road III to Lahdenväylä towards Lahti. **Model: V = a + b x q** *(q_{range} = 112-576 veh/h)*

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.003	70.59	0.01
$V_{15\%}$	-0.005	64.03	0.02
$V_{85\%}$	-0.011	81.71	0.09
V_{light}	-0.002	70.72	0.01
V_{heavy}	-0.010	65.13	0.04

$$V_{average} = 71.61 - 0.0054\,Q - 0.056\,(HV\%) \qquad R^2 = 0.10 \qquad (22)$$

$$V_{average} = 72.11 - 0.0061\,Q - 8.01\,D \qquad R^2 = 0.48 \qquad (23)$$

where D = 0 for light vehicles and 1 for heavy vehicles.

It can be seen that, as for the other ramps, the speed decreased with increasing flow rate. However, again, it should be noticed that the flow range is very small. According to *Equation (22)* the average speed of the vehicle on a ramp is not influenced only by traffic volume, it is also influenced by the HV%. Though the relation is too week to be useful, it can be postulated that the inclusion of the HV% in the equation improves the predictability of the average travel speed. According to *Equation (23)* the average speed difference between light and heavy vehicles was 8 km/h. The travel speeds as a function of flow rate for different proportions of heavy vehicles are illustrated in *Figure 29*.

The intercept of the model in *Equation (22)* is statistically significant but the coefficients of the flow rate and HV% are not statistically significant. On the other hand, the intercept and coefficient of the model in *Equation (23)* are statistically significant at the 0.00001 level but the coefficient of the flow rate is not.

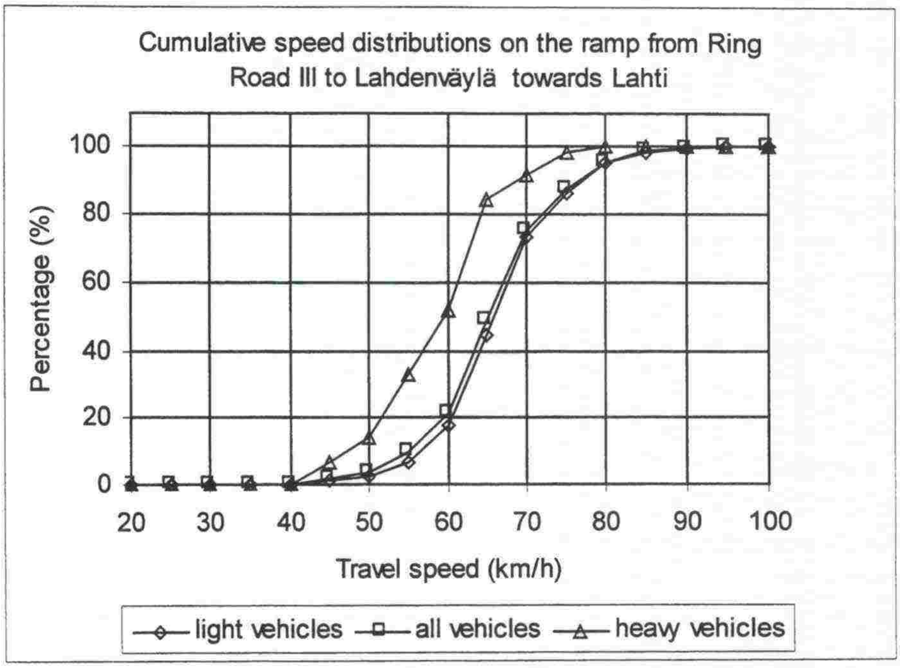

Figure 27. Cumulative speed distributions on the ramp from Ring Road III to Lahdenväylä towards Lahti.

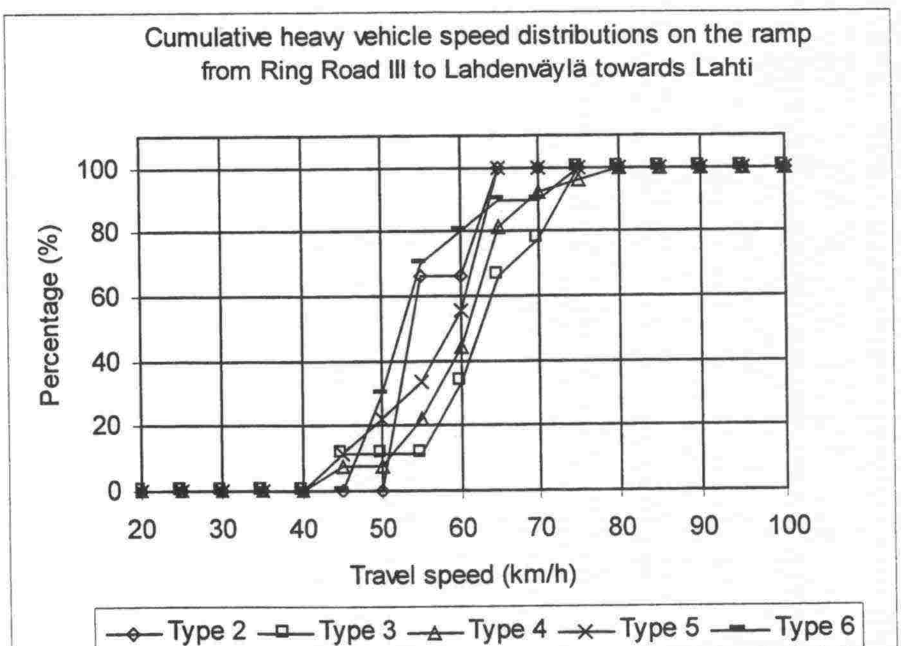

Figure 28. Cumulative heavy vehicle speed distributions on the ramp from Ring Road III to Lahdenväylä towards Lahti. The vehicle type numbers refer to section 7.1.

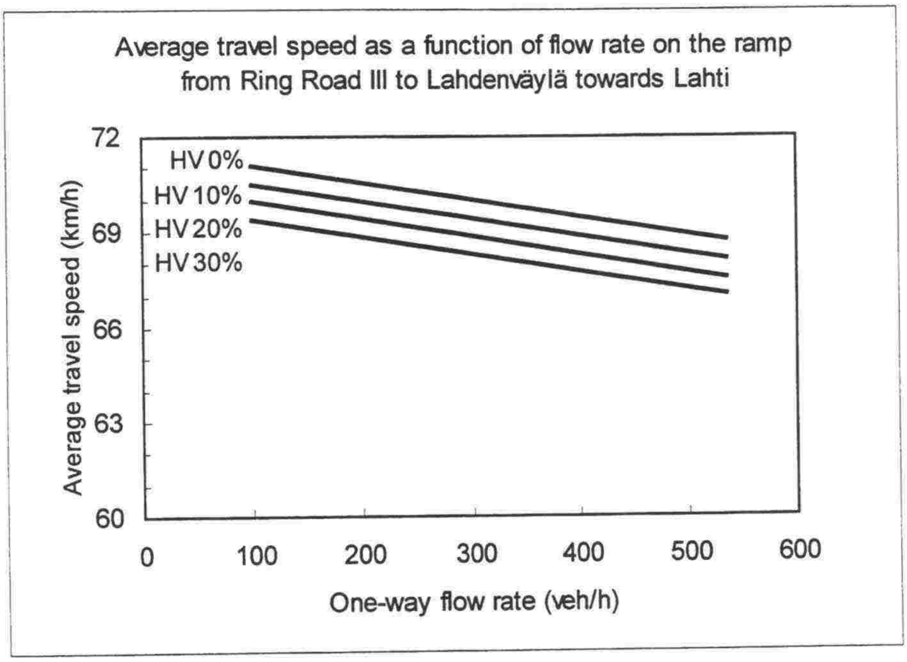

Figure 29. Average travel speed as a function of flow rate on the ramp from Ring Road III to Lahdenväylä towards Lahti. The speed lines are drawn using Equation (22).

7.3.4 Travel speed on the Sköldvik ramp at Porvoonväylä

The radius of the curve varies between 70 and 200 m for the jug-handle down-grade ramp from Sköldvik to Porvoonväylä. The grade is 1.8%. The configuration of the ramp is given in *Appendix D*. Two video cameras were used for collecting data. The distance between the two cameras was 468 m. A total of 1.5 hours of videotapes was recorded, from which the information of only 84 (55 light and 29 heavy) vehicles was obtained. The 5-minute flow rate had an average of 71 veh/h. The proportion of heavy vehicles varied between 17 and 50%.

The travel speed of the heavy vehicles varied between 35 and 85 km/h. The mode was around 45 km/h. The speed of the light vehicles fluctuated between 40 and 85 km/h and the mode was around 65 km/h (*Appendix C*). The 85th percentile speed of the heavy vehicles was 56 km/h and for the light vehicles 69 km/h. The 15th percentile speed of the heavy vehicles was 42 km/h and for the light vehicles 55 km/h. The speed difference between heavy and light vehicles varied between 0 and 17 km/h. The cumulative distributions of speeds for each vehicle type are presented in *Figures 30-31.*

The same calculations were made as for the other ramps, although some of them are not relevant because of the very low flow rate (*Table 18, Equations 24-25*).

Table 18. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on the Sköldvik ramp at Porvoonväylä towards Helsinki. ***Model: V = a + b x q*** *(q_{range} = 24-238 veh/h)*

Speed level	Coefficient (b)	Intercept (c)	R^2
$V_{average}$	-0.104	67.4	0.32
$V_{15\%}$	-0.153	64.7	0.37
$V_{85\%}$	-0.021	69.3	0.01
V_{light}	-0.040	68.2	0.10
V_{heavy}	-0.062	57.1	0.10

$$V_{average} = 71.93 - 0.0386\ Q - 0.247\ (HV\%) \qquad R^2 = 0.35 \qquad (24)$$

$$V_{average} = 68.68 - 0.0490\ Q - 12.58\ D \qquad R^2 = 0.72 \qquad (25)$$

where D = 0 for light vehicle and 1 for heavy vehicle.

The coefficients of flow rate and heavy vehicles of the model in *Equation (24)* were not statistically significant. The intercept and the coefficient of the dummy variable for the model in *Equation (25)* were statistically significant but the coefficient of the flow rate was not statistically significant. Based on these analyses it is impossible to say anything, because of very few observations. Based on the model in *Equation (25)* the heavy vehicles on the Sköldvik ramp maintained about 13 km/h lower speed than the light vehicles.

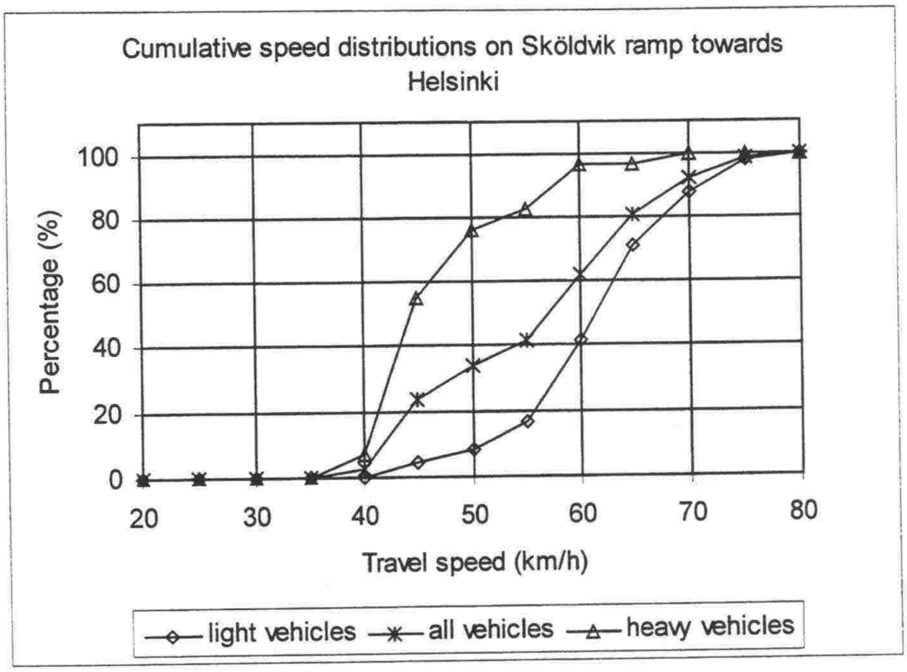

Figure 30. Cumulative speed distributions on the Sköldvik ramp at Porvoonväylä towards Helsinki.

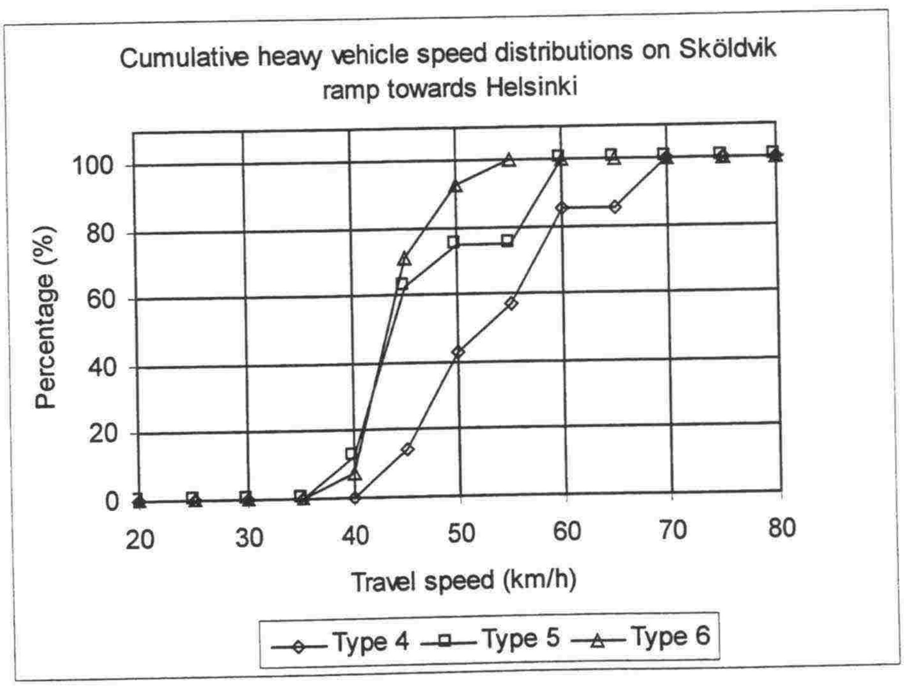

Figure 31. Cumulative heavy vehicle speed distributions on the Sköldvik ramp at Porvoonväylä towards Helsinki. The vehicle type numbers refer to section 7.1.

7.3.5 Travel speed on the ramp from Ring Road I to Länsiväylä

The grade of the jug-handle downgrade ramp from Ring Road I (Karhusaarentie) to Länsiväylä is 2.2%. The radius of the curve of the ramp varies between 100 m and 300 m. The speed limit is 60 km/h. The configuration of the ramp is given in *Appendix D*. Two video cameras were positioned in two successive locations for collecting information of the vehicles on the ramp. The distance between the two cameras was 625 m. A total of 1 hour 15 minutes of videotape was recorded from which the information of 686 (580 light and 106 heavy) vehicles was obtained. All data were analysed based on 5 minutes average. The 5-minute flow rate had an average of 635 veh/h. The proportion of heavy vehicles (HV%) had an average value of 16 % and 90% of the values were between 0 and 22%.

The travel speed of the heavy vehicles fluctuated between 25 and 70 km/h. The mode was around 55 km/h. The travel speed of the light vehicles fluctuated between 40 and 75 km/h and the mode was just over 55 km/*h (Appendix C*). The 85th percentile speed was 55 km/h for heavy vehicles and 62 km/h for light vehicles. The corresponding values for the15th percentile speed were 47 and 49 km/h. The speed difference between light and heavy vehicles varied between 0 and 5 km/h. The cumulative distributions of speeds for each vehicle type are presented in *Figures 32-33.*

The same relationships as for the other ramps were calculated (*Table 19, Equations 26-27*). As we see in *Table 21* the R^2 values of the regression models are very small which means that the relationship between speed and flow rate is very weak in this flow area.

Table 19. Trave speed (V, km/h) as a function of flow rate (q, veh/h) on the ramp from Ring Road I (Karhusaarentie) to Länsiväylä towards Helsinki. ***Model: V = a + b x q*** *(q_{range} = 460-976 veh/h)*

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.007	62.9	0.19
$V_{15\%}$	-0.002	54.5	0.01
$V_{85\%}$	-0.001	65.5	0.01
V_{light}	-0.005	62.8	0.12
V_{heavy}	-0.006	58.7	0.03

$$V_{average} = 63.17 - 0.007\,Q - 0.0205\,(HV\%) \qquad R^2 = 0.19 \qquad (26)$$

$$V_{average} = 62.90 - 0.0057\,Q - 4.33\,D \qquad R^2 = 0.52 \qquad (27)$$

where D = 0 for light vehicles and 1 for heavy vehicles.

Both models are statistically significant at the 0.00001 level, but the coefficients of flow rate are not statistically significant. Based on the analyses, it is obvious that average travel speeds of the vehicles decrease as the flow rate and proportion of heavy vehicles increase. On this ramp the average speed of the heavy vehicles was about 5 km/h lower than the average speed of the light vehicles.

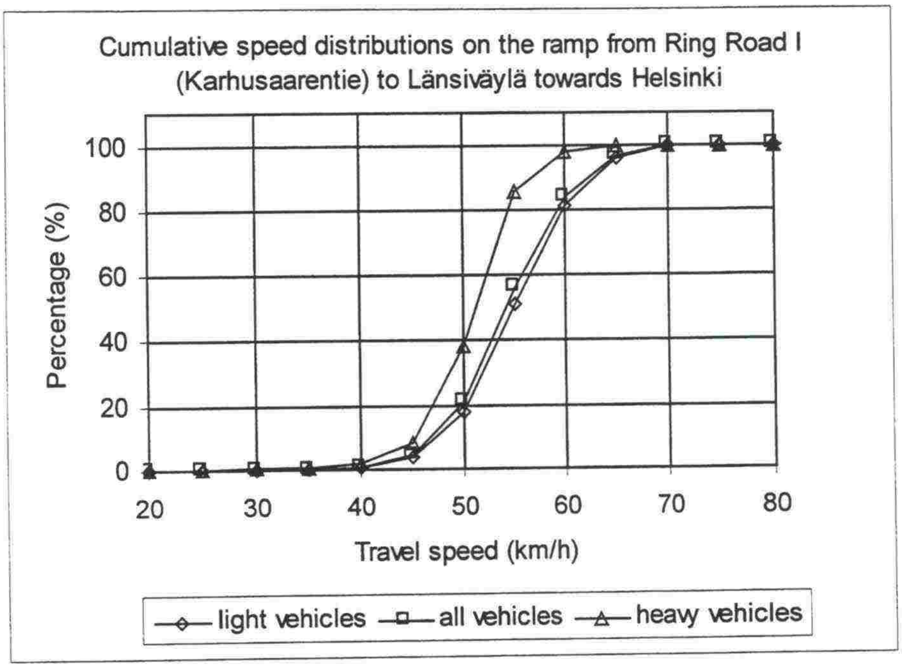

Figure 32. Cumulative speed distributions on the ramp from Ring Road I (Karhusaarentie) to Länsiväylä towards Helsinki.

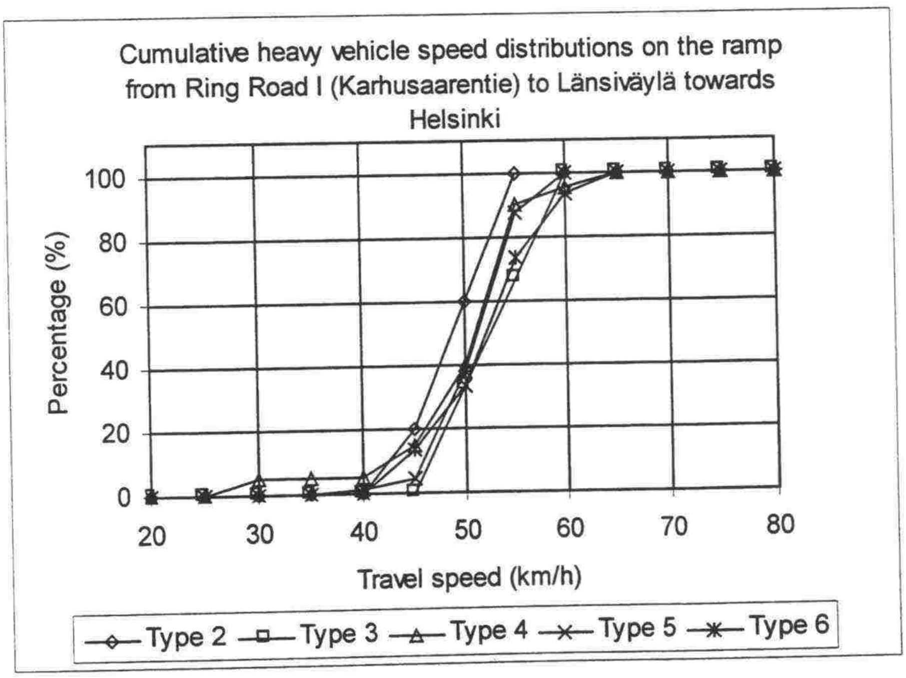

Figure 33. Cumulative heavy vehicle speed distributions on the ramp from Ring Road I (Karhusaarentie) to Länsiväylä towards Helsinki. The vehicle type numbers refer to section 7.1.

7.4 Travel speed on upgrades and downgrades

7.4.1 Travel speed on the Tuomarila upgrade and downgrade

The travel speeds on the upgrade and downgrade at Tuomarila on Turunväylä were measured using video cameras. The speed limit on the grades is 120 km/h and the grade is 1.6%. The distance between the cameras was 1,259 m on the downgrade and 1,141 m on the upgrade.

At the upgrade a total of 1.5 hours of videotapes including the information of 626 (444 light and 182 heavy) vehicles was recorded. The 5-minute flow rate (for both lanes together) had an average of 734 veh/h. The average HV% was 20% and 90 % of the values were between 0 and 32%. At downgrade a total of 3 hours of videotapes including the information of 5,108 (4,757 light and 351 heavy) vehicles was recorded and from which travel speed and flow rate were calculated. The 5-minute flow rate had an average of 2,305 veh/h (for both lanes together). The 5-minute rate of HV% had an average value of 8% and it varied between 3 and 33%.

The average travel speed on the upgrade was about 92 km/h. The 85th percentile speed for the light vehicles was about 105 km/h and for the heavy vehicles about 87 km/h. The corresponding values for the 15th percentile speed were 82 and 74 km/h. On the downgrade the average travel speed was about 100 km/h. The 85th percentile speed for the light vehicles was about 113 km/h and for the heavy vehicles about 95 km/h. The corresponding values for the 15th percentile speed were 88 and 77 km/h.

The cumulative speed distributions are shown in *Figures 34-37.* The travel speeds of the light vehicles on the upgrade fluctuated between 65 and 125 km/h and of the heavy vehicles between 63 and 106 km/h. The mode was around 95 km/h for light vehicles and around 83 km/h for heavy vehicles. The travel speeds of the light vehicles on the downgrade fluctuated between 70 and 125 km/h and of the heavy vehicles between 66 and 105 km/h. The mode of the speeds of the light vehicles was around 100 km/h and of the heavy vehicles around 85 km/h (*Appendix C*).

The speed differences between heavy vehicles and light vehicles varied between 0 and 16 km/h on the upgrade. On the downgrade the speed differences between light vehicles and heavy vehicles varied between 0 and 14 km/h.

The relationships between average travel speed, 85th percentile speed, 15th percentile speed, speed of light vehicles and speed of heavy vehicles, and flow rate are shown using linear regression equations. The parameters of the regression models are given in *Tables 20 and 21*. The regression lines are almost horizontal and the R^2 values quite low indicating that the relationship between speed and flow rate on Tuomarila upgrade and downgrade was very poor. The regression lines for the average travel speed as a function of flow rate are given in *Appendix E.*

Table 20. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on Tuomarila upgrade. ***Model: V = a + b x q*** *(q_{range} = 612-973 veh/h)*

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.0139	100.5	0.10
$V_{15\%}$	-0.0173	92.6	0.19
$V_{85\%}$	-0.0135	115.8	0.09
V_{light}	-0.0148	107.3	0.15
V_{heavy}	-0.0042	84.8	0.01

Table 21. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on Tuomarila downgrade at Turunväylä. ***Model: V = a + b x q*** *(q_{range} =1480-2724 veh/h)*

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.0003	99.9	0.01
$V_{15\%}$	0.0004	88.4	0.03
$V_{85\%}$	-0.0007	113.0	0.04
V_{light}	-0.0011	103.0	0.14
V_{heavy}	-0.0021	88.0	0.01

The relationship between average travel speed V (km/h), flow rate Q (veh/h), and HV% are shown using multiple regression analyses in *Equations (28) and (29)*.

$$V_{average,\ upgrade} = 100.37 - 0.0059\ Q - 0.301\ (HV\%) \qquad R^2 = 0.33 \qquad (28)$$

$$V_{average,\ downgrade} = 104.58 - 0.0016\ Q - 0.306\ (HV\%) \qquad R^2 = 0.69 \qquad (29)$$

The intercepts and coefficients for heavy vehicles were statistically significant ($P<0.00001$) but the coefficients of the flow rates were not statistically significant. The regression equations indicate that the average speed of the vehicles decreases as the flow rate and HV% increase.

Average speed differences between light and heavy vehicles on both the upgrade and the downgrade were estimated using linear regression with a dummy variable. The coefficients of the flow rate were not statistically significant but the intercepts and coefficients of the dummy variable were statistically significant at 0.00001 level. The models are given below:

$$V_{average,\ upgrade} = 99.79 - 0.0047\ Q - 14.52\ D \qquad R^2 = 0.88 \qquad (30)$$

$$V_{average,\ downgrade} = 102.1 - 0.0006\ Q - 13.14\ D \qquad R^2 = 0.98 \qquad (31)$$

According to the analyses the speed difference between light and heavy vehicles was about 15 km/h on Tuomarila upgrade and 13 km/h on Tuomarila downgrade.

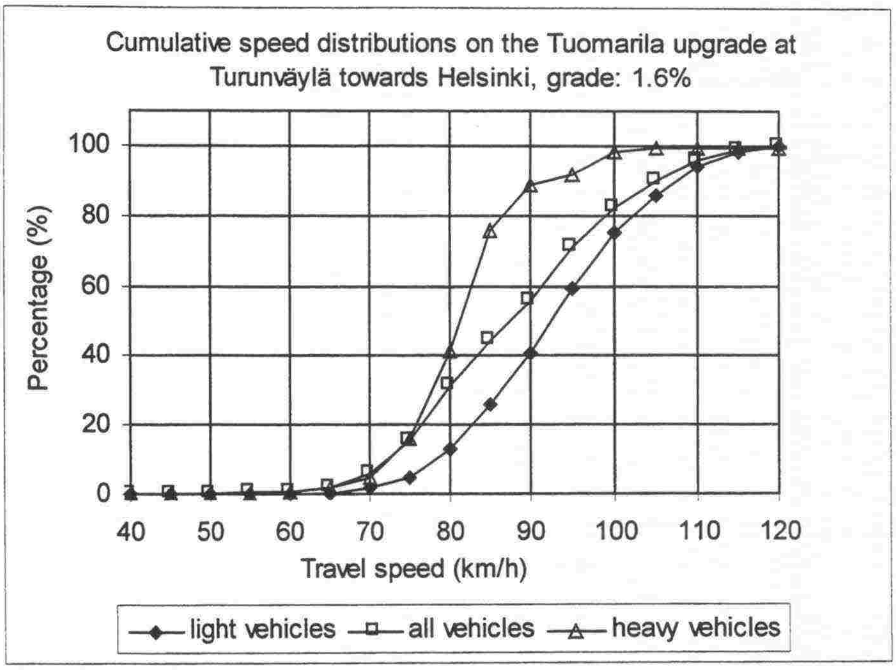

Figure 34. Cumulative speed distributions on the Tuomarila upgrade at Turunväylä towards Helsinki.

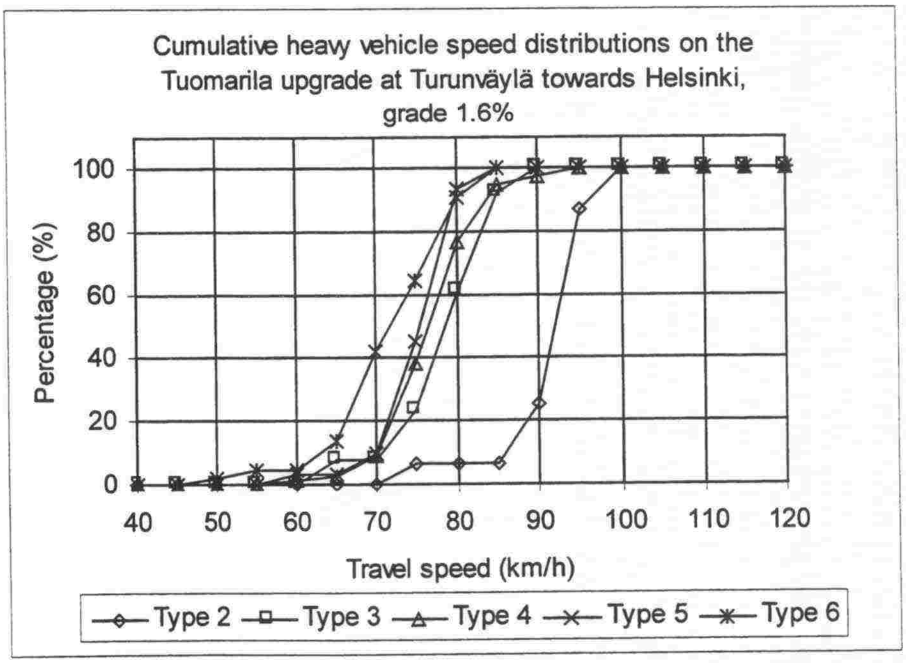

Figure 35. Cumulative heavy vehicle speed distributions on the Tuomarila upgrade at Turunväylä towards Helsinki. The vehicle type numbers refer to section 7.1.

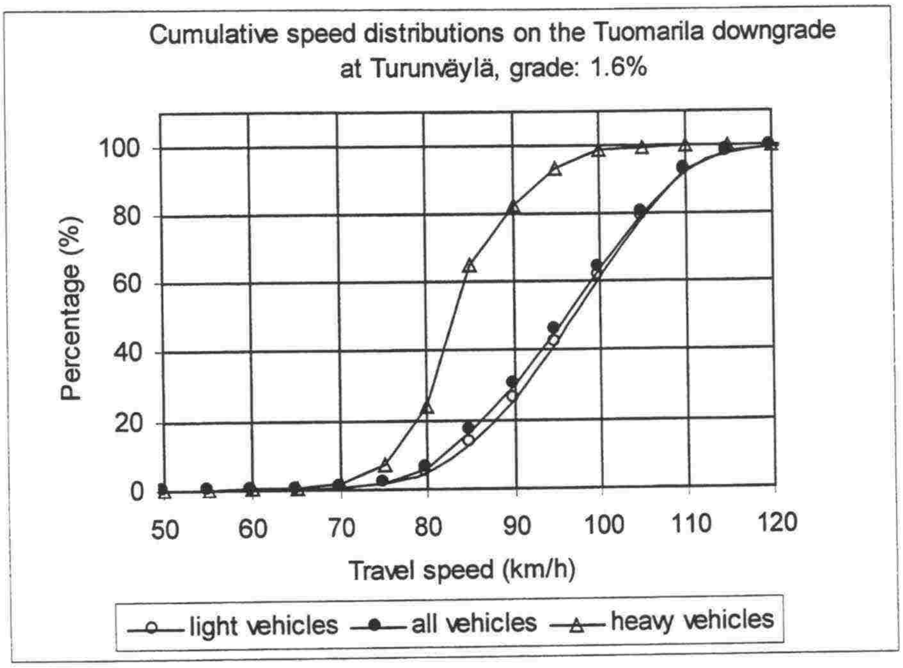

Figure 36. Cumulative speed distributions on the Tuomarila downgrade towards Turku on Turunväylä.

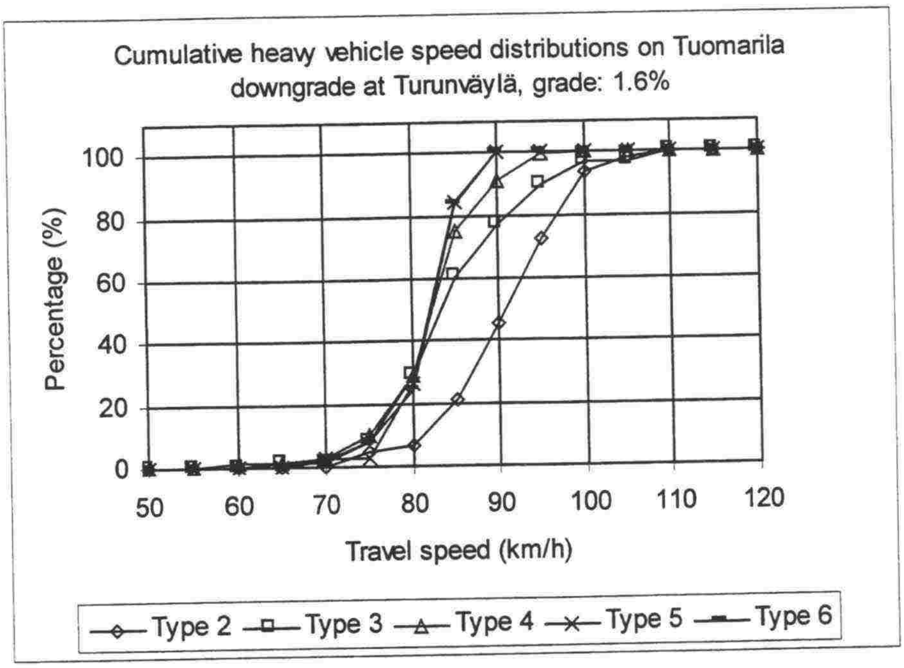

Figure 37. Cumulative heavy vehicle speed distributions on the Tuomarila downgrade towards Turku on Turunväylä. The vehicle type numbers refer to section 7.1.

7.4.2 Travel speeds on Kalkkikallio upgrade and downgrade

The Kalkkikallio upgrade and downgrade on Ring Road III are quite steep grades for Finnish conditions. The speed limit was 80 km/h and the grade was 5%. The distance between the video cameras was 1,100 m for the downgrade and 976 m for the upgrade.

For the upgrade towards east the data included information of 739 (568 light and 171 heavy) vehicles. The 5-minute flow rate on the upgrade had an average of 786 veh/h (for both lanes together). The 5-minute rate of HV% had an average value of 22 % and varied between 18 and 29%. For the downgrade towards west the data included information of 725 (614 light and 111 heavy) vehicles. The 5-minute flow rate on the downgrade had an average of 908 veh/h (for both lanes together). The 5-minute rate of HV% had an average value of 17% and varied between 10 and 23%.

The travel speeds of the heavy vehicles were found to be clearly lower than the travel speeds of the light vehicles both on the upgrade and downgrade. The speed differences usually varied between 0 and 8 km/h on the upgrade and between 0 and 11 km/h on the downgrade. The cumulative speed distributions on the upgrade are illustrated in *Figures 38-39*. The travel speeds of the vehicle types 3-5 varied between 55 and 90 km/h on the upgrade. The speeds of the buses (type 2) fluctuated between 70 and 110 km/h and the speeds of the trucks with full trailers (type 6) between 54 and 85 km/h. On the upgrade the speeds of the light vehicles fluctuated between 60 and 110 km/h and of the heavy vehicles between 55 and 100 km/h. The mode of the speeds of both the light and the heavy vehicles was around 80 km/h (*Appendix C*).

On the downgrade the speeds of the buses fluctuated between 71 and 95 km/h and the speeds of the trucks with semi-trailer varied between 60 and 95 km/h. The overall speed of the light vehicles on the downgrade fluctuated between 65 and 115 km/h and of the heavy vehicles between 55 and 100 km/h. The mode for both the light and heavy vehicles was around 85 km/h (*Appendix C*). The cumulative speed distributions on the downgrade are presented in *Figures 40-41*. Average travel speed as a function of flow rate is given in *Appendix E*.

A simple linear regression analysis for the average travel speed was made. *Tables 22* and *23* show the results of the regression analyses. As could be expected the travel speeds were higher on the downgrade than on the upgrade. The 85th percentile speeds for heavy vehicles on the downgrade were 3.5 km/h higher and for light vehicles 4.1 km/h higher than those on the upgrade. The 15th percentile speeds for heavy vehicles on the downgrade were about 5.2 km/h higher and for light vehicles about 8.5 km/h higher than those on the upgrade.

Table 22. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on Kalkkikallio upgrade at Ring Road III. ***Model: V = a + b x q*** *(q $_{range}$ = 540-1128 veh/h)*

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.006	87.9	0.18
$V_{15\%}$	-0.005	80.1	0.22
$V_{85\%}$	-0.007	96.5	0.09
V_{light}	-0.006	89.5	0.16
V_{heavy}	-0.011	85.3	0.37

Table 23. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on Kalkkikallio downgrade at Ring Road III. ***Model: V = a + b x q*** *(q $_{range}$ = 708-1155 veh/h)*

Speed level	Coefficient (b)	Intercept (a)	R^2
$V_{average}$	-0.003	90.3	0.13
$V_{15\%}$	-0.001	82.2	0.01
$V_{85\%}$	-0.006	102.2	0.19
V_{light}	-0.003	91.7	0.20
V_{heavy}	-0.007	89.8	0.22

The relationship between travel speed V (km/h), flow rate Q (veh/h), and proportion of heavy vehicles (HV%) were established using regression analyses (*Equations 32 and 33*). The coefficients of the models were all significant at 0.00001 level. It should be noted that the regression equations are based on small numbers of observations. Though the coefficients are not statistically significant, it is obvious that flow rate and percentage of heavy vehicles have a decreasing effect on travel speeds. The average travel speed as a function of flow rate for different proportion of heavy vehicles is illustrated in *Figures 42-43*.

$$V_{average,\ upgrade} = 93.1 - 0.0029\ Q - 0.38\ (HV\%) \qquad R^2 = 0.29 \qquad (32)$$
$$V_{average,\ downgrade} = 92.3 - 0.0028\ Q - 0.11\ (HV\%) \qquad R^2 = 0.31 \qquad (33)$$

Average speed differences between light and heavy vehicles on the upgrade and the downgrade were estimated using linear regression with dummy variables. The intercepts of the models were statistically significant but the coefficients of flow rate were not statistically significant at 0.00001 level. The models are given below:

$$V_{average,\ upgrade} = 91.39 - 0.0082\ Q - 7.99\ D \qquad R^2 = 0.80 \qquad (34)$$
$$V_{average,\ downgrade} = 93.37 - 0.0052\ Q - 5.22\ D \qquad R^2 = 0.77 \qquad (35)$$

According to the models light vehicles maintained about 8 km/h higher speed on upgrade and 5 km/h higher speed on downgrade compared to heavy vehicles.

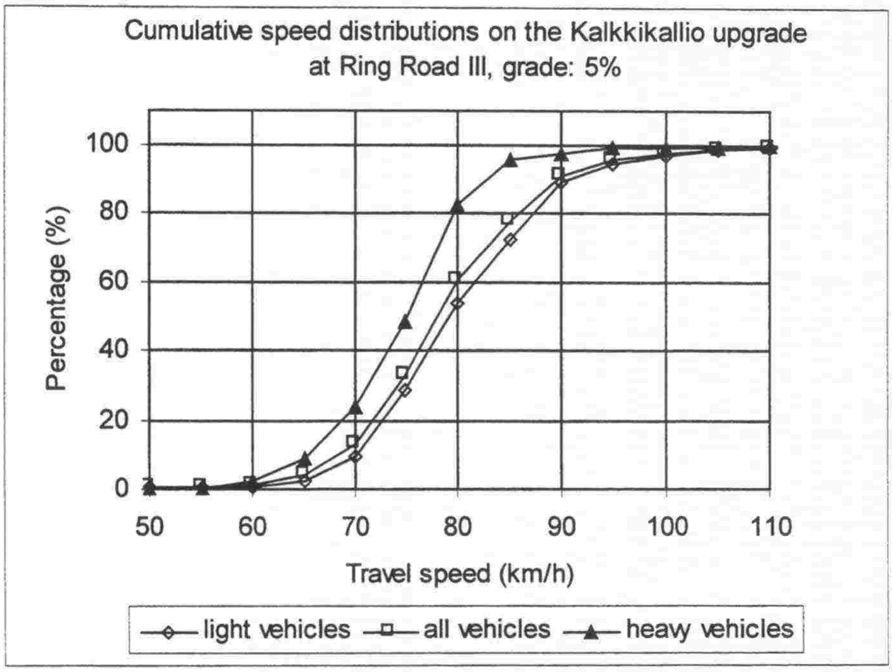

Figure 38. Cumulative speed distributions on Kalkkikallio upgrade at Ring Road III towards east.

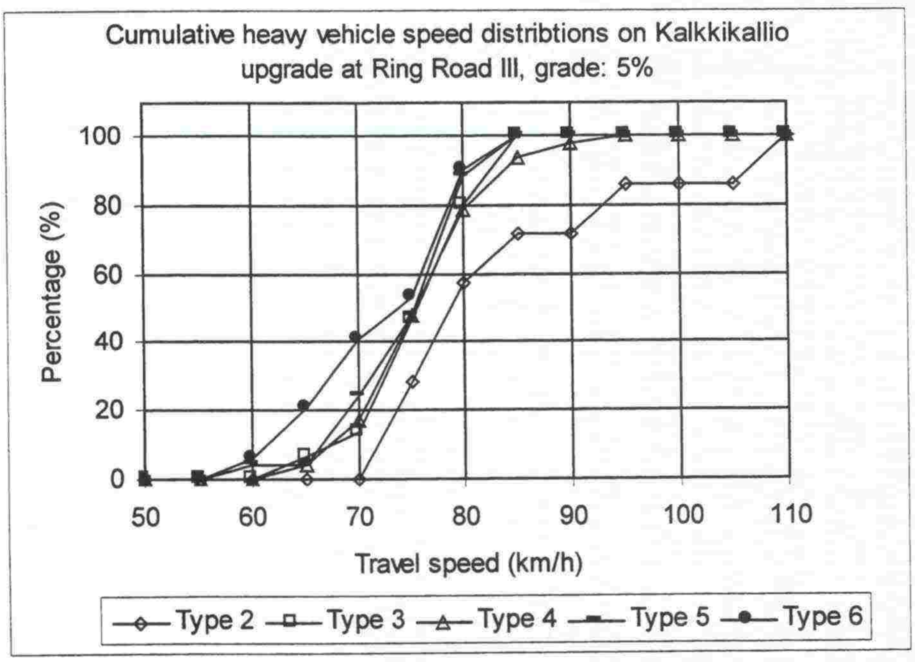

Figure 39. Cumulative heavy vehicle speed distributions on Kalkkikallio upgrade at Ring Road III towards east. The vehicle type numbers refer to section 7.1.

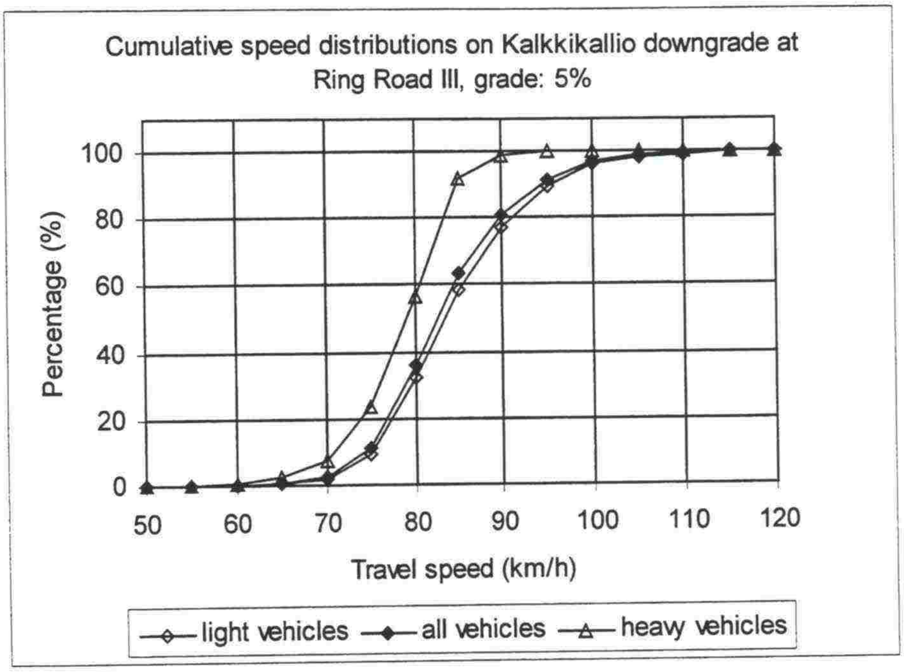

Figure 40. Cumulative speed distributions on Kalkkikallio downgrade at Ring Road III towards west.

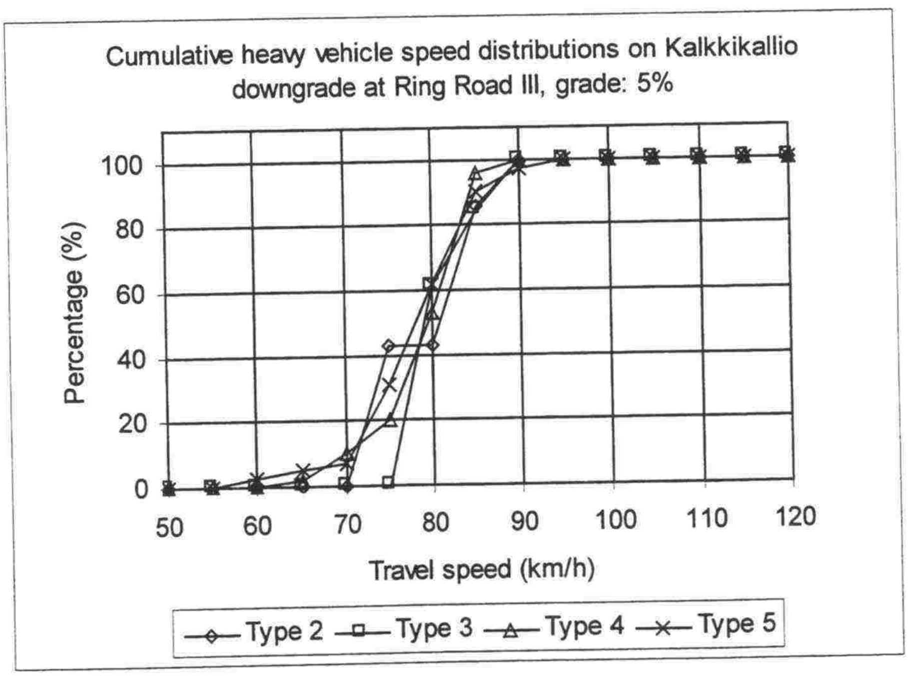

Figure 41. Cumulative heavy vehicle speed distributions on Kalkkikallio downgrade at Ring Road III towards west. The vehicle type numbers refer to section 7.1.

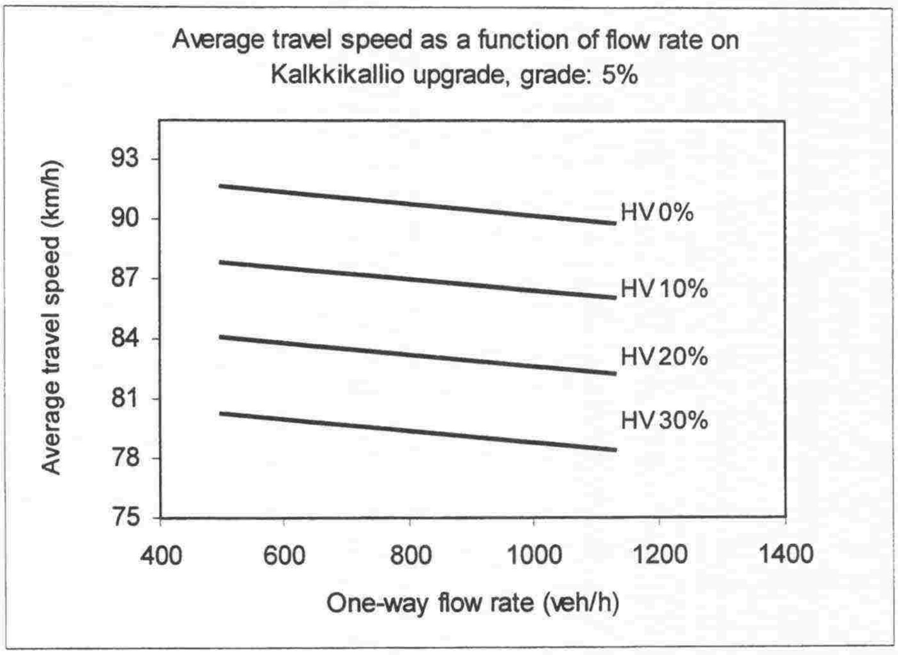

Figure 42. Travel speed as a function of flow rate on Kalkkikallio upgrade at Ring Road III with different proportions of heavy vehicles. The speed lines were drawn using Equation (32).

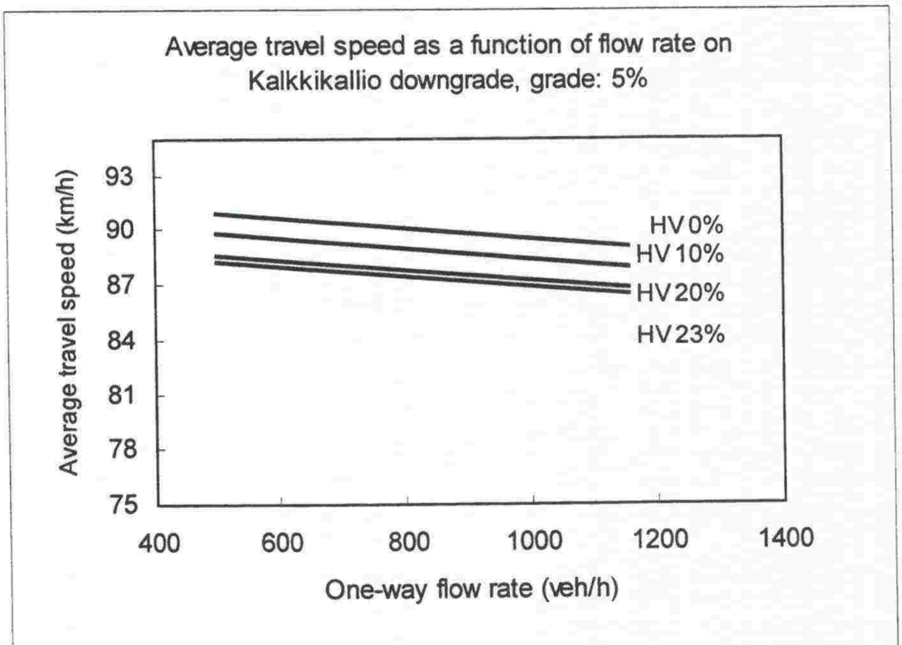

Figure 43. Travel speed as a function of flow rate on Kalkkikallio downgrade at Ring Road III with different proportions of heavy vehicles. The speed lines were drawn using Equation (33).

7.4.3 Travel speeds on an upgrade and downgrade at Hämeenlinnanväylä

The speed limit on the studied grades at Hämeenlinnanväylä is 120 km/h and the grades are quite gentle, only 1.2%. The distance between the video cameras was 3,413 m for the downgrade and 3,399 m for the upgrade. Data were collected as described earlier. The measurement period was 1 hour 10 minutes. For the upgrade towards Hämeenlinna the data included information of 595 (508 light and 87 heavy) vehicles and for the downgrade towards Helsinki the data included information of 563 (469 light and 94 heavy) vehicles. The 5-minute flow rate had an average of 538 veh/h on the upgrade and 448 veh/h on the downgrade. The 5-minute rate of heavy vehicle percentage (HV%) had an average value of 16% and 90% of the values were between 0 and 22% on the downgrade. The maximum 5-minute rate of HV% was 27% on the downgrade. On the upgrade the 5-minute rate of HV% had an average value of 14% and 90% of the values were between 0 and 19%. The maximum 5-minute rate of HV% was 20%.

The cumulative travel speed distributions are shown in *Figures 44-47*. The travel speeds of the light vehicles were found to be clearly higher than the travel speeds of the heavy vehicles both on the upgrade and the downgrade. The speed differences varied between 0 and 35 km/h on the upgrade and between 0 and 37 km/h on the downgrade.

The mode of the travel speeds of the heavy vehicles on the downgrade was around 85 km/h and on the upgrade around 84 km/h. The mode of the speeds of the light vehicles was around 120 km/h as well on the upgrade as on the downgrade. The overall speeds of the light vehicles fluctuated between 80 and 140 km/h on the downgrade and between 75 and 140 km/h on the upgrade. The travel speeds of the heavy vehicles fluctuated between 75 and 110 km/h on the downgrade and between 70 and 110 km/h on the upgrade (*Appendix C*).

The 85th percentile speeds of heavy vehicles on the downgrade were about 4 km/h higher than on the upgrade. The 15th percentile speeds of the heavy vehicles on the downgrade were about 3 km/h higher than on the upgrade. The 85th percentile speeds of the light vehicles on the downgrade were about 3.5 km/h higher than on the upgrade. The 15th percentile speeds on the downgrade were about 103 km/h and on the upgrade about 96 km/h.

The relationships between average travel speed, 85th percentile speed, 15th percentile speed, speed of heavy vehicles and light vehicles and flow rate are shown using simple linear regression in *Tables 24 - 25*. The R^2 values of the models were very small, which means that the relationship between flow rate and travel speed on this upgrade and downgrade is very poor. One reason behind that is few observations and another reason can be the narrow range of flow rate. The regression lines for average travel speed as a function of flow rate are given in *Appendix E*.

Table 24. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on the upgrade at Hämeenlinnanväylä. ***Model: V = a + b x q*** *(q_{range} = 396-780 veh/h)*

Speed level	coefficient (b)	Intercept (a)	R^2
V average	-0.004	111.5	0.02
V15%	-0.014	99.6	0.10
V85%	-0.003	127.9	0.02
V light	-0.001	114.1	0.01
V heavy	-0.015	96.1	0.25

Table 25. Travel speed (V, km/h) as a function of flow rate (q, veh/h) on the downgrade at Hämeenlinnanväylä. ***Model: V = a + b x q*** *(q_{range} = 264-680 veh/h)*

Speed level	coefficient (b)	Intercept (a)	R^2
V average	-0.003	113.4	0.01
V15%	-0.006	97.02	0.02
V85%	-0.002	130.8	0.02
V light	-0.005	121.3	0.03
V heavy	-0.004	92.0	0.02

The impact of heavy vehicles and traffic flow on average travel speed is also shown using regression analysis (*Equations 36 and 37*). The intercepts and the coefficients of the heavy vehicles were statistically significant at the 0.00001 level but the coefficients of the flow rate were not statistically significant. According to the models it can be postulated that the average travel speed decreases when the proportion of heavy vehicles and the flow rate increase.

$$V_{average,\ upgrade} = 115.4 - 0.0026\ Q - 0.32\ (HV\%) \qquad R^2 = 0.33 \qquad (36)$$

$$V_{average,\ downgrade} = 118.7 - 0.0024\ Q - 0.33\ (HV\%) \qquad R^2 = 0.49 \qquad (37)$$

Average speed difference between light and heavy vehicles were estimated using linear regression with dummy variable. These models are statistically significant but the coefficients of the flow rate of these models were not statistically significant. The models are given below:

$$V_{average,\ upgrade} = 118.2 - 0.0079\ Q - 26.1\ D \qquad R^2 = 0.97 \qquad (38)$$
$$V_{average,\ downgrade} = 118.7 - 0.0024\ Q - 29.1\ D \qquad R^2 = 0.95 \qquad (39)$$

According to the dummy models the speed difference between light and heavy vehicle was higher on downgrade than on upgrade. Light vehicles maintained 29 km/h higher average speed on the downgrade and 26 km/h on the upgrade compared to heavy vehicles.

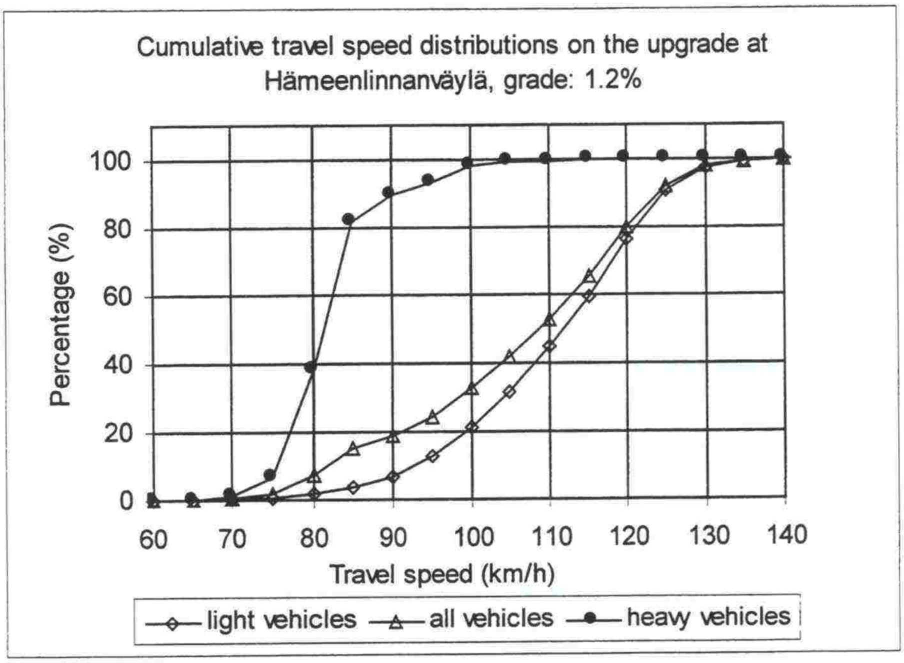

Figure 44. Cumulative speed distributions on the upgrade at Hämeenlinnanväylä towards Hämeenlinna.

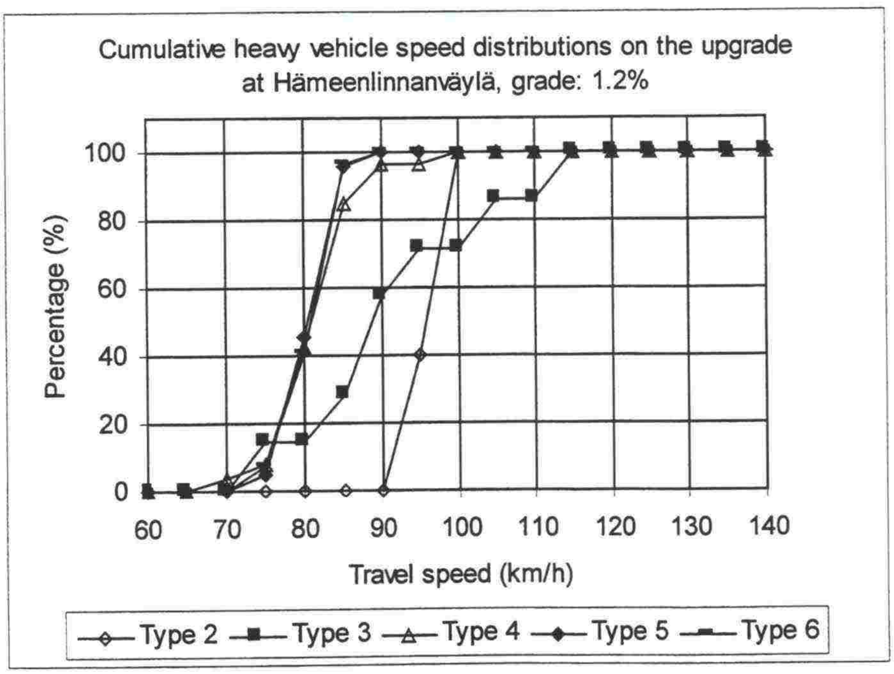

Figure 45. Cumulative heavy vehicle speed distributions on the upgrade at Hämeenlinnanväylä towards Hämeenlinna. The vehicle type numbers refer to section 7.1.

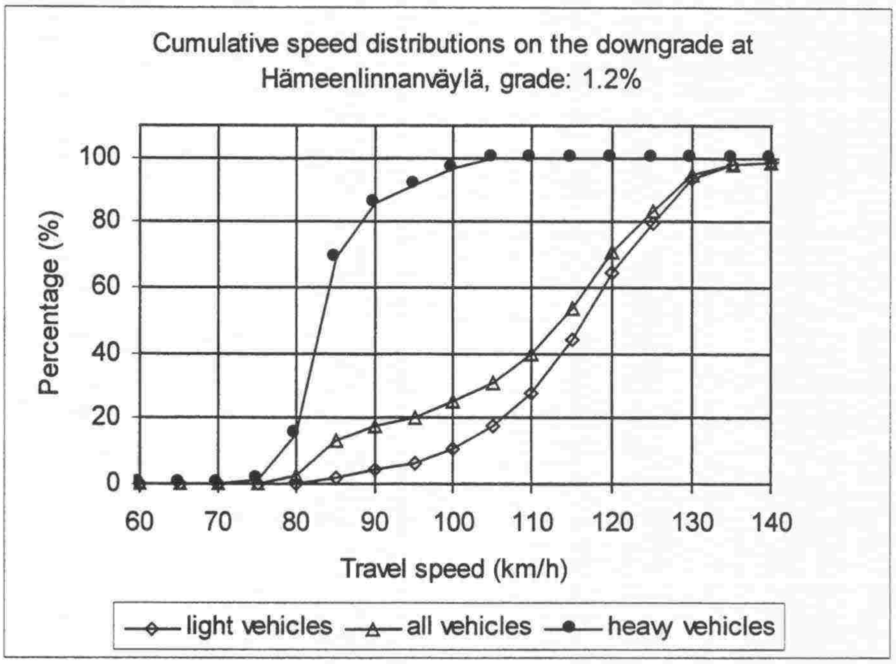

Figure 46. Cumulative speed distributions on the downgrade at Hämeenlinnanväylä towards Helsinki.

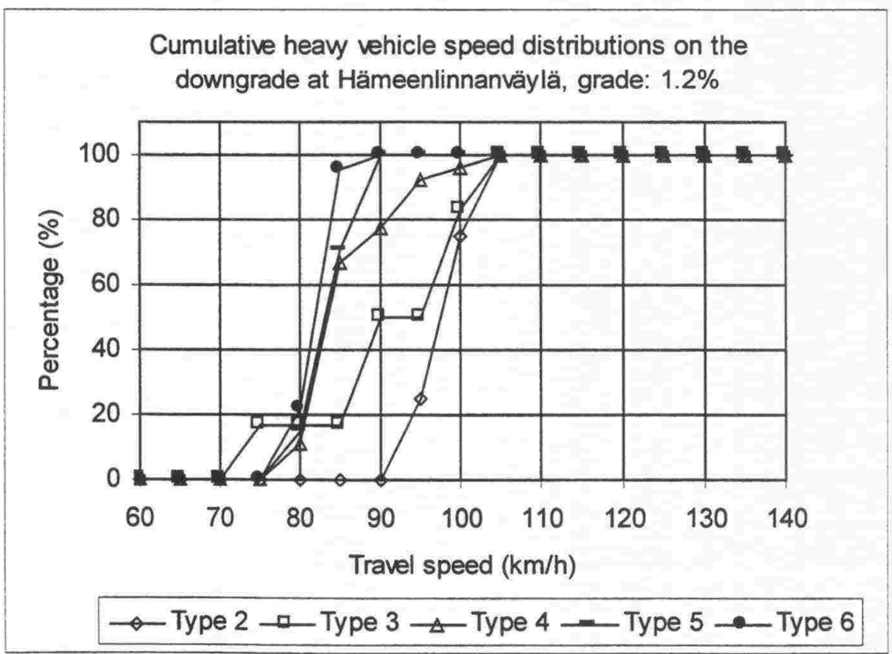

Figure 47. Cumulative heavy vehicle speed distributions on the downgrade at Hämeenlinnanväylä towards Helsinki. The vehicle type numbers refer to section 7.1.

8 SPACE MEAN SPEED AND FLOW RATE

8.1 Space mean speed

Space mean speed (V_s) is an important measure of the quality of traffic flow. It can be obtained by taking the harmonic mean of spot speeds, which can be obtained from local point measurements. The point measurement data were collected from the Automatic Traffic Measurement System (LAM) and analysed using a softwear program to get information in 15 minute intervals regarding space mean speed, flow rate, proportion of heavy vehicles, headway, platoon percentages, platoon lengths, and speed distributions. The Automatic Traffic Measurement System is installed and controlled by the Finnish National Road Administration. The data collection points, locations, numbers, directions, and times are given in *Appendix F*.

Vehicles were separated into two types, namely heavy vehicles and light vehicles. The vehicle type was deduced from the length of the vehicle. A vehicle was considered to be a light vehicle when the length was less than or equal to 6.0 m. Consequently, a vehicle which length was greater than 6.0 m was considered to be a heavy vehicle. The speeds were separated into free speeds, constrained speeds, light vehicle speeds, and heavy vehicle speeds.

Free speed – the speed of a vehicle was considered to be free if the time headway to the preceding vehicle was greater than 5 seconds.

Constrained speed – the speed of a vehicle was considered to be constrained speed if the time headway to the preceding vehicle was less than or equal to 5 seconds.

The relationship between space mean speed and flow rate was analysed with linear regression analyses for all flow conditions.

8.2 Space mean speed on Ring Road III

A total of 70 hours of point measurement data were collected including information of 190,649 vehicles from the automatic data collection point number 128 (LAM 128) which is situated on Ring Road III (*Appendix F*). The speed limit was 80 km/h on the road section in question. On Ring Road III the 15-minute flow rate had an average of 919 veh/h on the basic lane and 670 veh/h on the passing lane towards Vantaa. Towards Kirkkonummi the 15-minute flow rate had an average of 889 veh/h on the basic lane and 735 veh/h on the passing lane.

The proportion of heavy vehicles (HV%) fluctuated between 8 and 32% on the basic lane and between 0 and 18% on the passing lane towards Vantaa. The average HV% towards Vantaa was 20% on the basic lane and 6% on the passing lane. Towards Kirkkonummi the proportion of heavy vehicles fluctuated between 8 and 35% on the basic lane and between 1 and 24% on the passing lane. The average HV% was 21% on the basic lane and 7% on the passing lane.

The 15th percentile speed was 2-3 times higher at morning peak than at evening peak towards Vantaa. The 85th percentile speed was also higher at morning peak than at evening peak towards Vantaa. Towards Kirkkonummi the 15th and 85th percentile speeds were higher at evening peak than at morning peak. The 15th and 85th percentile speeds are shown in *Table 26*.

Table 26. The 15th and 85th percentile speeds on basic lane and passing lane on Ring Road III (LAM 128).

15th percentile speed	Lane type	Morning peak	Evening peak	Non-peak hour
Vantaa	Basic lane	45.1	15.1	70.2
Vantaa	Passing lane	39.6	18.9	80.9
Kirkkonummi	Basic lane	50.9	55.2	66.1
Kirkkonummi	Passing lane	45.1	71.4	77.3
85th percentile speed	Lane type	Morning peak	Evening peak	Non-peak hour
Vantaa	Basic lane	72	56	85
Vantaa	Passing lane	78	66	96
Kirkkonummi	Basic lane	77	80	84
Kirkkonummi	Passing lane	86	87	93

Space mean speed and flow rate

The relationships between space mean speed and flow rate were established using linear regression. The results from the regression analyses are presented in *Tables 27-28*. The intercepts towards Kirkkonummi were below 100 and fluctuated between 80 and 91. Towards Vantaa the intercepts varied between 84 and 94. The slopes of the models for the direction towards Vantaa fluctuated between 3.7 and 15.5 km/h per 1,000 veh/hour and for the direction towards Kirkkonummi between 2.5 and 16.5 km/h per 1,000 veh/h. Logically the intercept of the free speed could be higher than the intercept of the constrained speed. As we see from *Tables 27-28*, the intercepts of the constrained speeds were somewhat higher than the intercepts of the free speed. The reason for that is that the low speeds for the constrained vehicles at high flow areas increase the slope and the intercept of the regression lines.

Table 27. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) at LAM 128 on Ring Road III towards Vantaa. ***Model: $V_s = a + b \times q$*** *($q_{range, basic}$ = 432-1289 veh/h, $q_{range, passing}$ = 148-1529 veh/h, $q_{range, both}$ = 657-2827 veh/h/direction).*

Speed type	Lane type	Intercept a	Coefficient b	R^2	Statistical significance
V_{all}	Basic lane	92.14	-0.0161	0.42	Yes
V_{free}	Basic lane	87.83	-0.0088	0.14	Yes
$V_{constraint}$	Basic lane	89.33	-0.0131	0.30	Yes
V_{light}	Basic lane	92.35	-0.0155	0.44	Yes
V_{heavy}	Basic lane	88.87	-0.0151	0.36	Yes
V_{all}	Passing lane	94.38	-0.0137	0.69	Yes
V_{free}	Passing lane	92.24	-0.0051	0.28	Yes
$V_{constraint}$	Passing lane	92.35	-0.0117	0.59	Yes
V_{light}	Passing lane	94.14	-0.0127	0.72	Yes
V_{heavy}	Passing lane	89.25	-0.0087	0.28	Yes
V_{all}	Both lanes	90.28	-0.0069	0.53	Yes
V_{free}	Both lanes	88.59	-0.0037	0.26	Yes
$V_{constraint}$	Both lanes	86.31	-0.0047	0.35	Yes
V_{light}	Both lanes	89.11	-0.0054	0.48	Yes
V_{heavy}	Both lanes	84.44	-0.0056	0.50	Yes

Table 28. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) at LAM 128 on Ring Road III towards Kirkkonummi. ***Model: $V_s = a + b \times q$*** *($q_{range, basic}$ = 416-1382 veh/h, $q_{range, passing}$ = 116-1540 veh/h, $q_{range, both}$ = 566-2849 veh/h/direction)*

Speed type	Lane type	Intercept a	Coefficient b	R^2	Statistical significance
V_{all}	Basic lane	87.14	-0.0152	0.54	Yes
V_{free}	Basic lane	82.86	-0.0066	0.12	Yes
$V_{constraint}$	Basic lane	86.28	-0.0149	0.51	Yes
V_{light}	Basic lane	89.48	-0.0165	0.62	Yes
V_{heavy}	Basic lane	80.95	-0.0131	0.36	Yes
V_{all}	Passing lane	91.13	-0.0090	0.59	Yes
V_{free}	Passing lane	89.53	-0.0025	0.10	Yes
$V_{constraint}$	Passing lane	90.43	-0.0088	0.53	Yes
V_{light}	Passing lane	91.59	-0.0093	0.62	Yes
V_{heavy}	Passing lane	87.90	-0.0100	0.29	Yes
V_{all}	Both lanes	85.21	-0.0046	0.52	Yes
V_{free}	Both lanes	82.38	-0.0007	0.02	No
$V_{constraint}$	Both lanes	83.92	-0.0042	0.44	Yes
V_{light}	Both lanes	87.36	-0.0051	0.60	Yes
V_{heavy}	Both lanes	80.72	-0.0063	0.52	Yes

The relationship between space mean speed (V_s, km/h), flow rate (Q, veh/h), and proportion of heavy vehicles (HV%) has been established with linear regression. The regression models are given in *Equations (40)-(42)* for the direction towards Vantaa and in *Equations (43)-(45)* for the direction towards Kirkkonummi. The coefficients of the models were all significant at the 0.00001 level.

Regression models towards Vantaa:

$$V_{s\ (\text{basic lane})} = 93.49 - 0.0167\ Q - 0.0403\ (HV\%) \qquad R^2 = 0.43 \qquad (40)$$
$$V_{s\ (\text{passing lane})} = 95.83 - 0.0146\ Q - 0.1419\ (HV\%) \qquad R^2 = 0.70 \qquad (41)$$
$$V_{s\ (\text{both lanes})} = 92.94 - 0.0076\ Q - 0.0971\ (HV\%) \qquad R^2 = 0.54 \qquad (42)$$

Regression models towards Kirkkonummi:

$$V_{s\ (\text{basic lane})} = 96.40 - 0.0200\ Q - 0.2379\ (HV\%) \qquad R^2 = 0.64 \qquad (43)$$
$$V_{s\ (\text{passing lane})} = 93.51 - 0.0105\ Q - 0.1851\ (HV\%) \qquad R^2 = 0.61 \qquad (44)$$
$$V_{s\ (\text{both lanes})} = 91.84 - 0.0065\ Q - 0.2253\ (HV\%) \qquad R^2 = 0.57 \qquad (45)$$

The proportion of heavy vehicles (for both lanes) is slightly higher towards Kirkkonummi than towards Vantaa. Towards Vantaa HV% fluctuated between 6.2 and 27.2% and towards Kirkkonummi between 4.8 and 28.6%. The speed reduction coefficient for heavy vehicles is about 2.5 times higher towards Kirkkonummi than towards Vantaa when the data were aggregated for both lanes. This means that the effect of heavy vehicles on space mean speed is higher towards Kirkkonummi than towards Vantaa. One reason behind that is higher average percentage of heavy vehicles compared to the direction towards Vantaa.

Space mean speed and flow rate using piecewise regression

The relationship between speeds (V_s, km/h) and flow rates (Q, veh/h) for heavy and light vehicles were analysed using dummy variables (D) (see section 2.8). The piecewise regression models are given in *Equations (46)-(48)* for the direction Vantaa and in *Equations (49)-(51)* for the direction Kirkkonummi. The data set for these analyses contained flow rate and space mean speed (for light vehicles, heavy vehicles, all vehicles combined) for 15 minute intervals for each lane. Speed data of congested flow areas were also included in the analysis. For selecting the limit values of flow rate for the piecewise models the models were structured several times. Finally, the limit value of flow rate for Vantaa direction was selected 2,200 veh/h and for Kirkkonummi 1,700 veh/h because of the goodness of fit of the regression lines. The analyses were made for both lanes together.

Regression models towards Vantaa:

$$V_{light} = 93.30 - 0.0088 \times Q + 97.40 \times D - 0.0449 \times D \times Q \quad R^2 = 0.58 \quad (46)$$
$$V_{heavy} = 88.37 - 0.0088 \times Q + 77.63 \times D - 0.0355 \times D \times Q \quad R^2 = 0.56 \quad (47)$$

$$V_{all} = 90.40 - 0.0085 \times Q - 0.0424 \times D1 \times Q + 93.39 \times D + 3.79 \times D1 - 0.1096 \times D1 \times HV\% \quad R^2 = 0.56 \quad (48)$$

Regression models towards Kirkkonummi:

$$V_{light} = 82.94 - 0.0017 \times Q + 12.24 \times D - 0.0069 \times D \times Q \quad R^2 = 0.66 \quad (49)$$
$$V_{heavy} = 74.10 - 0.0010 \times Q + 13.43 \times D - 0.0083 \times D \times Q \quad R^2 = 0.57 \quad (50)$$

$$V_{all} = 84.32 - 0.0026 \times Q - 0.0066 \times D \times Q + 11.43 \times D + 1.51 \times D1 - 0.1731 \times D1 \times HV\% \quad R^2 = 0.63 \quad (51)$$

The value of the dummy variable D is 0 for flow rates below 2,200 veh/h/direction and 1 for flow rates above that. The value of D1 is 0 for the proportion of heavy vehicles (HV%) below 10% and 1 for HV% above that value for the direction towards Vantaa. For the direction towards Kirkkonummi the value of the dummy variable D is 0 for flow rates below 1,700 veh/h/direction and 1 above that. The value of D1 was the same as for the direction Vantaa.

Towards Vantaa, about 16% of the data points had flow rates above 2,200 veh/h/direction; the average flow rate was 2,471 with an average speed of 58 km/h, and an average of 10% heavy vehicles. Based on the model this speed for the same parameters is 60.6 km/h. Towards Kirkkonummi, about 37% of the data points had a flow rate above 1,700 veh/h/direction and the average flow rate was 2,241 with an average speed of 74.8 km/h, and an average of 11% heavy vehicles. Based on the model this speed for the same parameters is 75 km/h. The space mean speeds as a function of flow rate are shown in *Figures 48-49*.

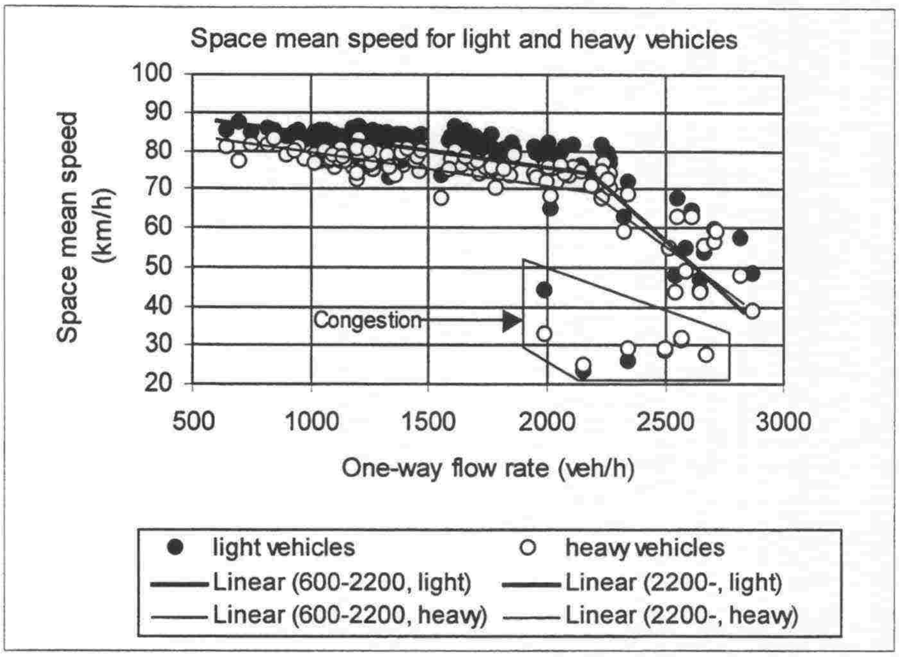

Figure 48. Space mean speed as a function of flow rate on Ring Road III at LAM 128 towards Vantaa. The piecewise regression lines were drawn using Equations (46) and (47).

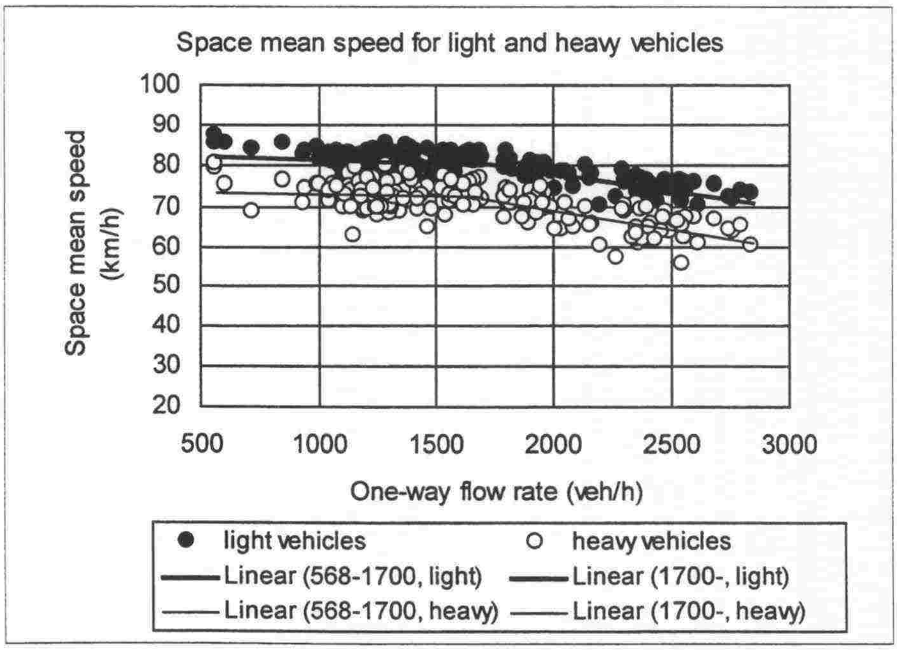

Figure 49. Space mean speed as a function of flow rate on Ring Road III at LAM 128 towards Kirkkonummi. The piecewise regression lines were drawn using Equation (49) and (50).

Space mean speed and flow rate using the van Aerde Model

From the traffic engineering point of view, to understand the differences between constrained and non-constrained traffic operations, it is necessary to evaluate the interdependencies between speed and flow using two-dimensional estimation procedure. A two-dimensional least square estimation procedure was successfully used in some earlier studies (Pursula 1995, Innamaa & Pursula 1998, Enberg & Mannan 1998). According to traffic flow theory, for each flow rate there are two different speed values, one for freely moving traffic and another for forced traffic. Like in earlier studies, the so-called van Aerde (1995) model was also used for two-dimensional speed-flow estimation in this study. The model is given below:

$$V=\frac{V_f}{2}-\frac{C_1}{2C_3}+\frac{1}{2C_3 d}\left(1-\sqrt{d^2\left[\left(C_3 V_f+C_1\right)^2+4C_2 C_3\right]-2d\left(C_3 V_f+C_1\right)+1}\right) \quad (52)$$

where:

V_f = free speed (km/h)
V = speed (km/h)
C_1 = fixed distance headway constant (km)
C_2 = first variable distance headway constant (km^2/h)
C_3 = second variable distance headway constant (h)
d = density (veh/km).

The coefficients of the traffic flow model and the network weights are related as follows (Pursula 1995):

$$C_1 = e^{w_1}, \qquad C_2 = e^{w_2}, \qquad C_3 = e^{w_3}, \qquad V_f = e^{w_4} \quad (53)$$

The initial values for the parameters were achieved on the basis of free speed and maximum density. Free speed was estimated using linear regression and is given in *Tables 27-28.*

Maximum density (jam density) was estimated using a general mathematical formulation given below:

$$d_{jam}=\frac{1000}{l_{vehicle}+l_{jam-spacing}} \quad (54)$$

where:

d_{jam} = jam density (veh/km)
$l_{vehicle}$ = average length of vehicle in traffic stream (m)
$l_{jam-spacing}$ = spacing between two vehicles in stationary traffic flow (m) .

The jam space length used for calculating jam density was 2.5 m. Average vehicle lengths were estimated based on vehicle compositions and their lengths in traffic stream. Initial values for the optimum speed (v_{opt}) and maximum traffic flow (capacity flow) were obtained by looking at the observation data set. The values for the parameter C_1, C_2, C_3 and V_f were estimated by using the initial values of free speed, maximum flow rate, and optimum speed and jam density. The estimation procedures of the parameters have been presented in detail in Pursula (1995).

According to estimation, speed at capacity towards Vantaa for light vehicles was about 10 km/h higher than for heavy vehicles (2,865 veh/h, 56.1 km/h for light and 2,865 veh/h, 46.7 km/h for heavy vehicles). Towards Kirkkonummi the corresponding value was about 10 km/h (2,790 veh/h, 64.8 km/h for light and 2,782 veh/h, 55 km/h for heavy vehicles). The estimated free flow speed for light vehicles was about 5-6 km/h higher than the speed for the heavy vehicles. The drop in speed from free flow conditions to the speed at capacity (critical speed) was less than 50% of free speed. Based on analysis it has been found that a drop in speed in the range of only about 20 to 45% of the initial free flow speed. The fundamental speed-flow relationships are shown in *Figures 50-51*. However, it can be noticed from the figures that speed at capacity has a significant effect on the shape of the speed-flow diagram. As the value of the speed at capacity is raised, the relationship that is generated also has an effect on the free flow regime (upper branch) of the speed-flow relationship and this area becomes increasingly more linear (slope is less steep). The estimated parameters for the speed-flow diagrams are given in *Table 29.*

Table 29. Parameters for two-dimensional estimation of the speed-flow relationship on Ring Road III (LAM 128).

Variable Description	Light vehicle Vantaa	Heay vehicle, Vantaa	Light vehicle, Kirkkonummi	Heavy vehicle, Kirkkonummi
Free speed	88.1	83.9	80.5	74.8
Parameter 1 (C1)	0.002564	0.001379	0.003531	0.003309
Parameter 1 (C2)	0.107827	0.202323	0.176484	0.03643
Parameter 1 (C3)	0.000244	0.000203	0.000287	0.000266
Speed at capacity	56.1	46.7	64.8	55.0
Volume at capacity	2863	2865	2790	2782
density at capacity	264	-	267	-

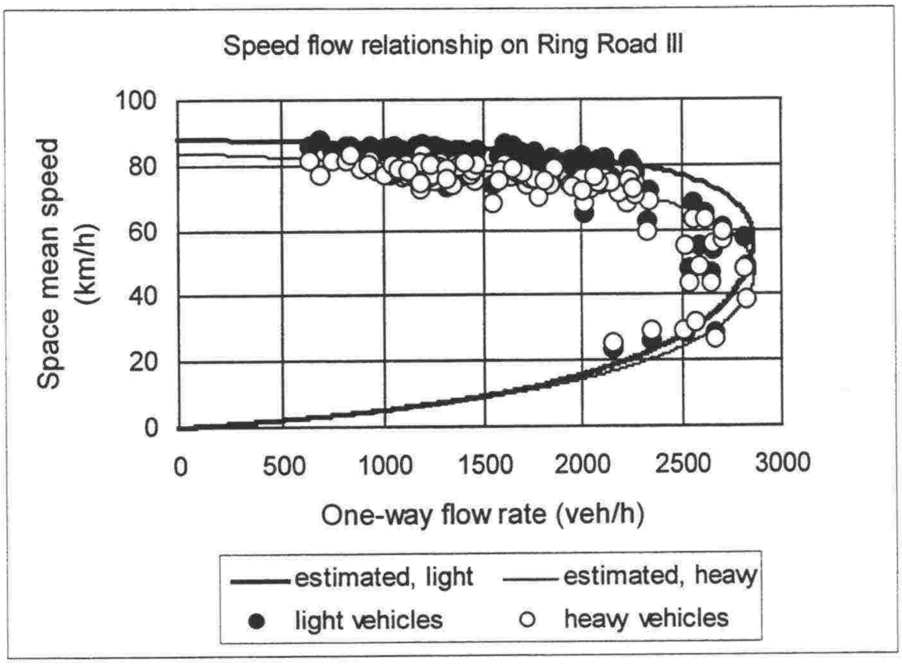

Figure 50. Space mean speed as a function of flow rate on Ring Road III at LAM 128 towards Vantaa.

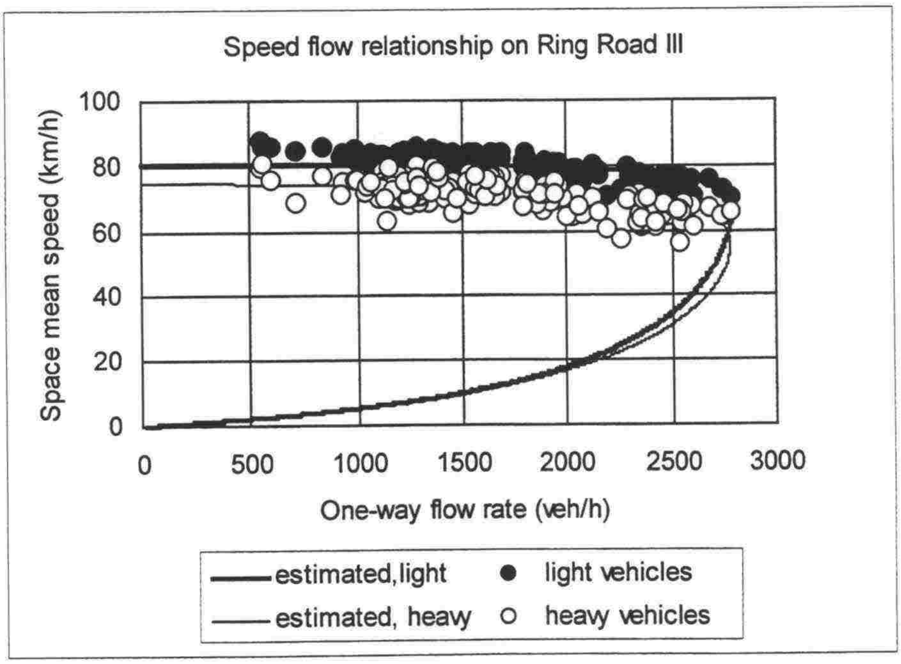

Figure 51. Space mean speed as a function of flow rate on Ring Road III at LAM 128 towards Vantaa.

Speed differences based on dummy model

Speed differences between light and heavy vehicle were estimated using dummy variables. The regression models were developed for each lane type and are given below:

Regression models towards Vantaa:

$$V_{\text{basic lane, Vantaa}} = 92.16 - 0.0152 \times Q - 3.11 \times D \quad R^2 = 0.52 \quad (55)$$
$$V_{\text{passing lane, Vantaa}} = 93.01 - 0.0107 \times Q - 2.63 \times D \quad R^2 = 0.51 \quad (56)$$
$$V_{\text{both lanes, Vantaa}} = 89.26 - 0.0055 \times Q - 4.97 \times D \quad R^2 = 0.69 \quad (57)$$

Regression models towards Kirkkonummi:

$$V_{\text{basic lane, Kirkkonummi}} = 89.10 - 0.0161 \times Q - 5.84 \times D \quad R^2 = 0.66 \quad (58)$$
$$V_{\text{passing lane, Kirkkonummi}} = 91.84 - 0.0097 \times Q - 4.20 \times D \quad R^2 = 0.47 \quad (59)$$
$$V_{\text{both lanes, Kirkkonummi}} = 88.33 - 0.0057 \times Q - 8.58 \times D \quad R^2 = 0.78 \quad (60)$$

The value of the dummy variable D is 0 for light vehicles and 1 for heavy vehicles. It can be seen that the speed decreased with increasing flow rate on both lanes. According to the models the space mean speeds of the heavy vehicles towards Vantaa were 3.1 km/h lower on the basic lane and 2.6 km/h lower on the passing lane than those of the light vehicles. When the regression analyses were made for both lanes together, the speed differences were found to be about 5 km/h. The speed difference between light and heavy vehicles on the basic lane towards Kirkkonummi was about twice the differences towards Vantaa. On basic lane the space mean speed of the heavy vehicles was about 6 km/h lower than the speed of light vehicles. The corresponding value on the passing lane was 4.2 km/h and on both lanes together about 9 km/h.

Speed distributions

The cumulative distributions of speeds for light vehicles and heavy vehicles are presented in *Figures 52-55*. Towards Vantaa the speed of the light vehicles fluctuated between 10 and 90 km/h at peak hours and between 60 and 100 km/h at off peak hours on the basic lane. The corresponding values on the passing lane varied between 10 and 110 km/h at peak hours and between 60 and 110 km/h at off peak hours. The speed of the heavy vehicles varied between 10 and 90 km/h at peak hours and between 50 and 90 km/h at off peak hours on the basic lane. The corresponding values on the passing lane varied between 10 and 100 km/h at peak hours and between 50 and 100 km/h at off peak hours on the passing lane. The mode of the speeds was around 80 km/h on the basic lane and around 90 km/h on the passing lane for both light and heavy vehicles. The speed difference between peak and off peak hours varied between 0 and 40 km/h for both light and heavy vehicles on the basic lane. On the passing lane the speed difference varied between 0 and 50 km/h for both vehicle types.

Towards Kirkkonummi the speeds of the light vehicles varied between 60 and 100 km/h on the basic lane and between 60 and 110 km/h on the passing lane.

The speed difference between peak and off peak hours varied between 0 and 5 km/h. The overall speeds of the heavy vehicles fluctuated between 40 and 90 km/h on the basic lane and between 50 and 90 km/h on the passing lane. The speed differences between peak hour and off peak hours varied between 0 and 3 km/h. The mode of the speed was around 80 km/h on the basic lane and around 90 km/h on the passing lane for both vehicle types.

It should be mentioned that towards Vantaa the traffic was affected by the down-stream traffic lights. The traffic towards Kirkkonummi was not affected very much because in this direction only left turning drivers have to actuate with traffic lights. This might be one reason, whey the speed level towards Kirkkonummi was not as low as towards Vantaa.

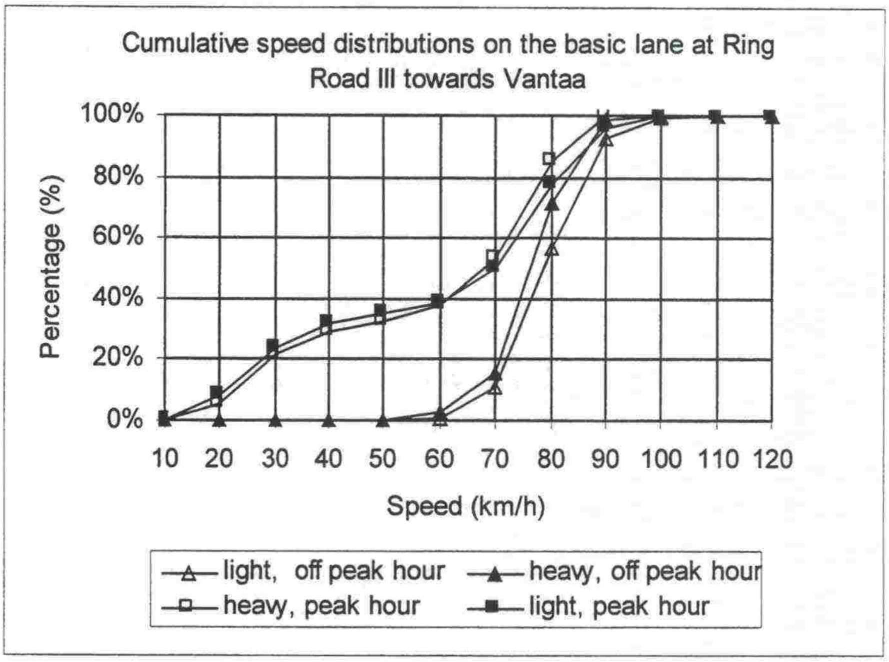

Figure 52. Cumulative speed distributions on the basic lane at Ring Road III towards Vantaa. The speed limit was 80 km/h.

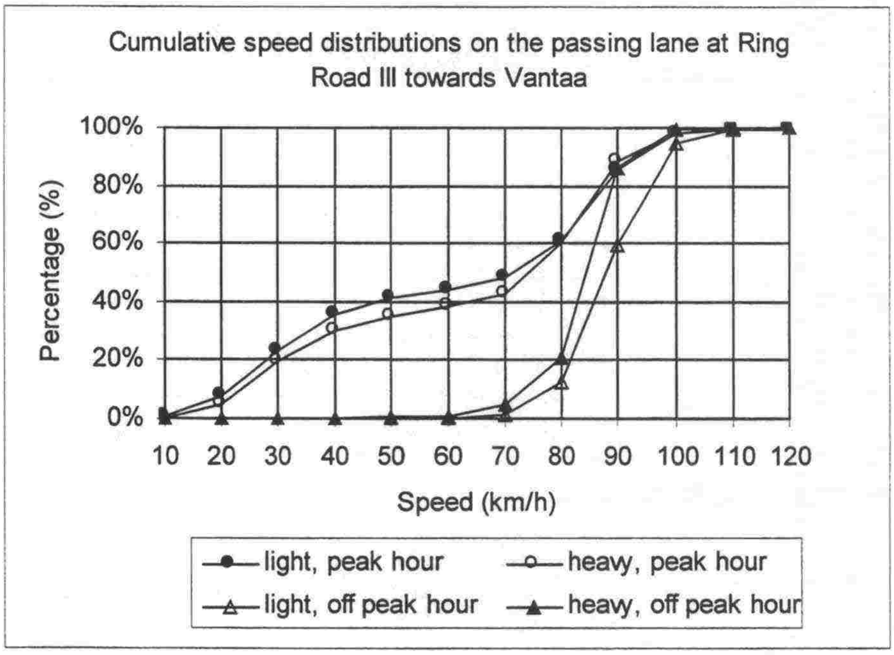

Figure 53. Cumulative speed distributions on the passing lane at Ring Road III towards Vantaa. The speed limit was 80 km/h.

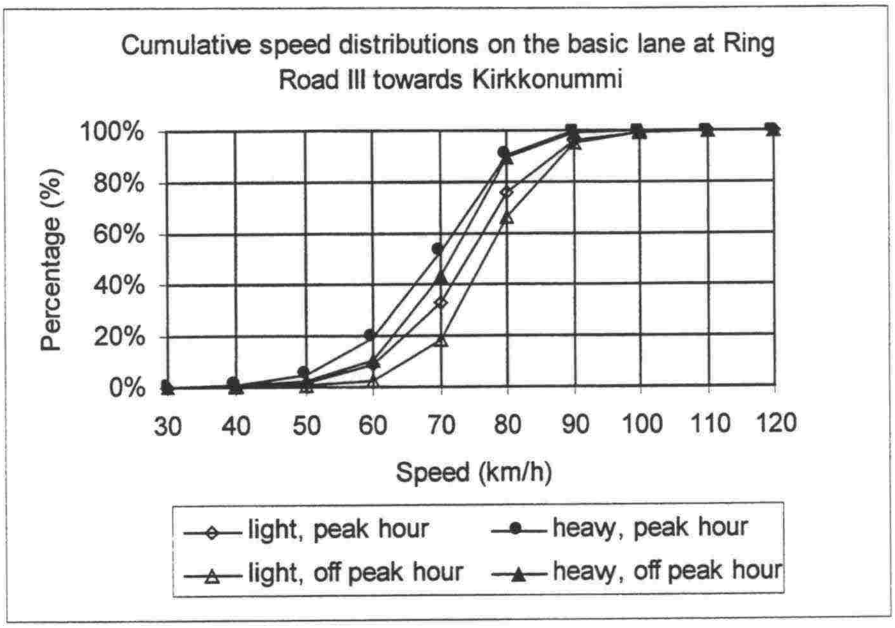

Figure 54. Cumulative speed distributions on the basic lane at Ring Road III towards Kirkkonummi. The speed limit was 80 km/h.

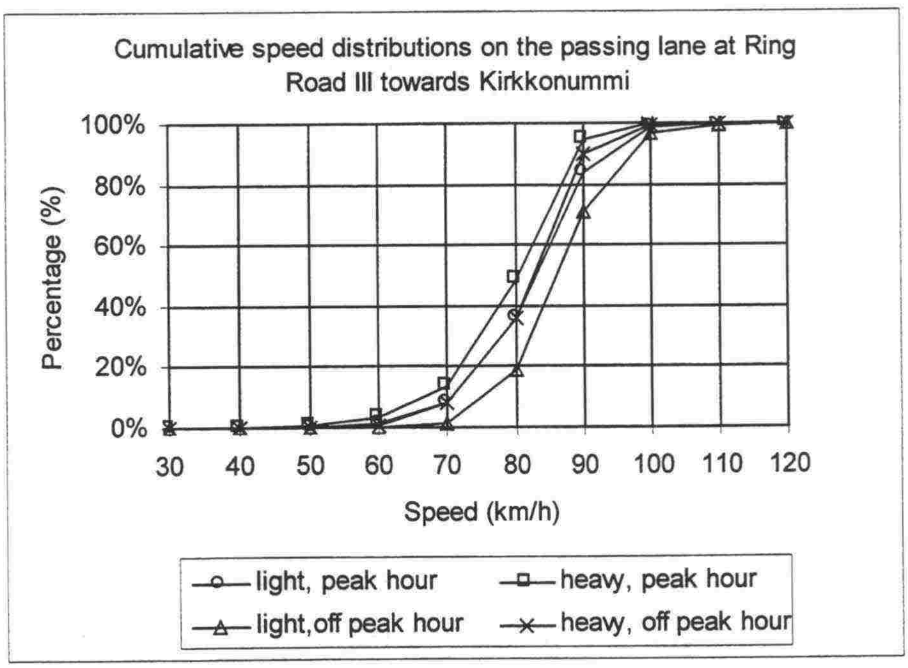

Figure 55. Cumulative speed distributions on the passing lane at Ring Road III towards Kirkkonummi. The speed limit was 80 km/h.

8.3 Space mean speed and flow rate on freeways

The speed flow relationships on the following freeways were studied: Länsiväylä, Lahdenväylä, Hämenlinnanväylä, Turunväylä, Tuusulanväylä and Porvoonväylä. A total of 588 hours of point measurement data were collected including information of 1,501,451 vehicles from the LAM points (*Appendix F*). Space mean speed as a function of flow rate was analysed using linear regression and the results are given in *Appendix G*. The results indicate that space mean speed usually decreases as flow rate increases. However, in some cases the results were the opposite or the regression lines were almost horizontal indicating that there was no linear relationship. The relationship between the speeds of the light and heavy vehicles and flow rate at different LAM points is presented in the figures in *Appendix H*. The speed reductions when the flow rate increased by 1,000 veh/h varied between 0.2 and 3.2 km/h on Hämeenlinnanväylä. The corresponding values varied between 1.6 and 5.4 km/h on Turunväylä, between 2.6 and 5.5 km/h on Lahdenväylä, between 2.8 and 3.5 km/h on Tuusulanväylä, and between 3.5 and 10 km/h on Länsiväylä. The space mean speeds and average flow rates at different LAM points are given in *Appendix I*.

The speed reductions of the heavy vehicles with increasing flow rates varied between 0.2 and 4.8 km/h on Turunväylä when both lanes were analysed together. The corresponding values varied between 0.1 and 2.8 km/h on Hämeenlinnanväylä, between 0.5 and 1.3 km/h on Lahdenväylä, between 1.5 and 4.4 km/h on Länsiväylä, and between 1.6 and 2.7 on Tuusulanväylä.

The relationship between space mean speed, flow rate, and proportion of heavy vehicles (HV%) has been established with linear regression. Possible unstable flow conditions were not separated from the data. The effects of road geometry on speed were not taken into account. The LAM sites are usually situated at locations with good geometry. The model form used in these analyses is not differ from the models described earlier. This is a linear model with space mean speed as dependent variable, and the flow rate of all vehicles and proportion of heavy vehicles as independent variables, as follows:

$$V_s = a + b \times Q + c \times HV\% \qquad (61)$$

where,

V_s	= space mean speed (km/h)
Q	= flow rate (veh/h)
HV%	= proportions of heavy vehicle (%)
a	= free flow speed (intercept)
b and c	= coefficients.

The model parameters a, b, and c are given in *Tables 31-32* for different LAM sites. Compared to other freeways the speed drop because of flow rate is high on Länsiväylä, 10 km/h per 1,000 veh/h. Speed reductions because of heavy vehicles are sometimes higher on the basic lane and sometimes higher on the passing lane. Even if the proportion of heavy vehicles on the passing lane is lower than on the basic lane, the speed reduction coefficient of HV% on the passing lane is sometimes twice the coefficient on the basic lane. Usually the speed level on the passing lane is higher than on the basic lane because most of the fast moving vehicles use the passing lane. Therefore if a few slow moving vehicles use the passing lane they will have an instantaneous effect on the speeds of the fast moving vehicles. This might be one reason why the speed reduction coefficient because of heavy vehicles sometimes is much higher on the passing lane. The effect of heavy vehicles on space mean speed also varied slightly between different highways.

The speed differences between light and heavy vehicles were estimated using a dummy variable in the following manner:

$$V_s = a + b \times q + c \times D \tag{62}$$

Where

V_s	= space mean speed (km/h)
a	= free speed (km/h)
q	= flow rate (veh/h)
D	= 0 for light vehicles and 1 for heavy vehicles
b, c	= coefficients.

The estimated parameters are given in *Tables 33-34*. It can be seen that in most cases the space mean speed decreases as flow rate increases. However, in some cases the results were the opposite.

According to the models the mean speed differences between light vehicles and heavy vehicles varied a lot among the LAM sites. These differences were sometimes higher on the basic lane and sometimes higher on the passing lane. When both lanes were analysed together the speed differences between light and heavy vehicles varied between 5.2 km/h and 26.7 km/h. The speed differences between light and heavy vehicles differ a lot because of different flow rate and speed limit. For example, on Länsiväylä the speed difference was 5.2 km/h when the range of flow rate was 445-4,302 veh/h and speed limit was 80 km/h, and 15 km/h when the flow rate was 248-1,474 veh/h and speed limit was 100 km/h. On Hämeenlinnanväylä, the speed difference between light vehicles and heavy vehicles at LAM 107 (speed limit 80 km/h) was 6 km/h for the flow range 183-3,633 veh/h. This difference at LAM 137 (speed limit 120 km/h) was 22.6 km/h for the flow range 184-3,275 veh/h.

Generally, heavy vehicles are not able to act according to high speed limits (80, 100 and 120 km/h) like light vehicles because of their lower acceleration, higher mass and size. On the other hand, the speeds of some heavy vehicles are limited to about 90 km/h using cruise electronic equipment. These are the reasons why the speed differences between light and heavy vehicles varied at different sites. Space mean speeds as a function of flow rate for light vehicles and heavy vehicles at different LAM sites are given in *Figures 56-57* and in *Appendix K*. Mean speed differences between light and heavy vehicles at different speed limit areas are summarised in *Table 30*.

Table 30. Speed differences between light and heavy vehicles at different speed limit areas.

Speed difference (km/h)	Speed limit 80 km/h	Speed limit 100 km/h	Speed limit 120 km/h
Basic lane	3-5 km/h	8-14 km/h	18-24 km/h
Passing lane	4-5 km/h	6-14 km/h	15-26 km/h
Both lanes	5-6 km/h	12-15 km/h	22-26 km/h

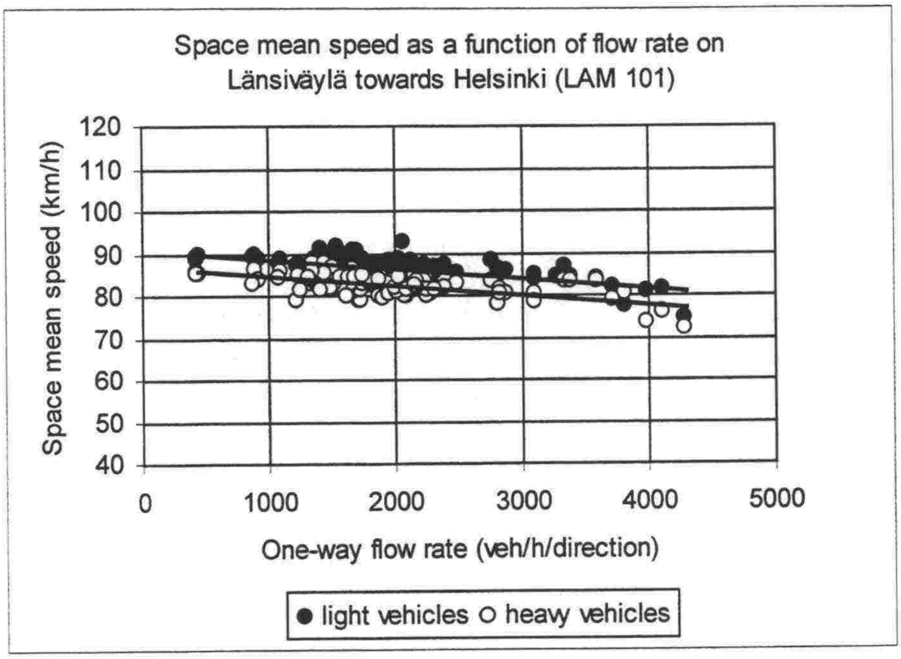

Figure 56. Space mean speed for light vehicles and heavy vehicles on Länsiväylä towards Helsinki. The speed limit was 80 km/h.

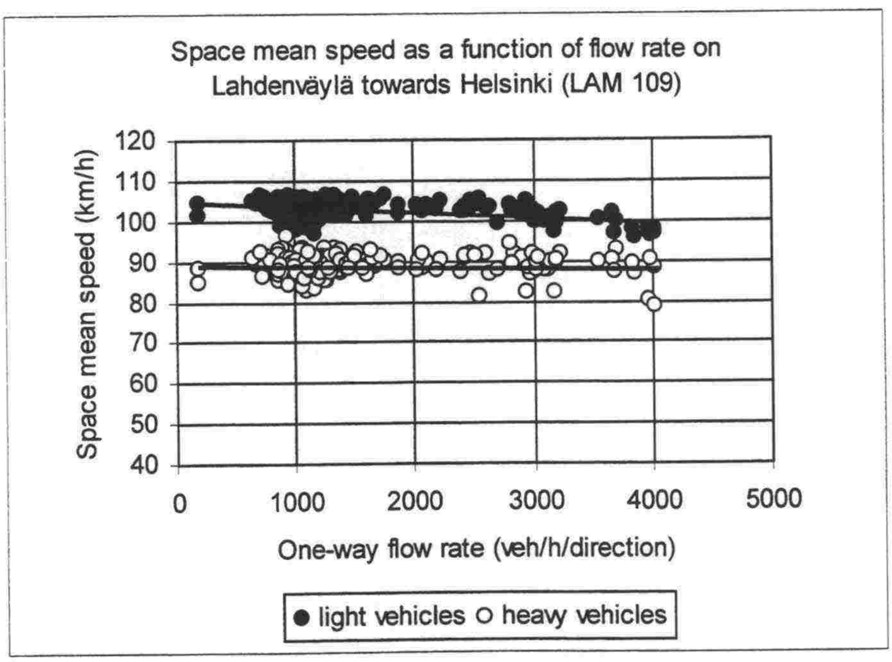

Figure 57. Space mean speed for light vehicles and heavy vehicles on Lahdenväylä towards Helsinki. The speed limit was 100 km/h.

Table 31. Space mean speed as a function of flow rate and HV% on different freeways. ***Model: V = a + b x q + c x HV%***

LAM sites	Location	Direction	Lane type	Intercept a	Coeffic. b	Coeffic. c	R^2	Flow range (veh/h)	Range of HV%	Speed limit (km/h)
101	Länsiväylä	Hki	Basic	95.44	-0.0101	-0.1448	0.48	366-1976	0-22	80
"	"	Hki	Passing	97.53	-0.0057	-0.0833	0.70	48-2347	0-10	80
"	"	Hki	Both	92.47	-0.0029	-0.1012	0.48	445-4302	0-20	80
"	"	Hki	Bus	90.82	-0.0240	-0.1063	0.46	44-486	15-92	80
102	Länsiväylä	Hki	Basic	97.77	-0.0006	-0.2432	0.49	224-981	1.8-22	100
"	"	Hki	Passing	107.41	-0.0057	-0.1816	0.10	24-493	0-9	100
"	"	Hki	Both	98.43	-0.0025	-0.2838	0.57	248-1474	1.5-18.5	100
104	Turunväylä	Tku	Basic	109.44	-0.0040	-0.2530	0.35	24-493	0.7-21.8	120
"	"	Tku	Passing	121.55	-0.0042	-0.1119	0.26	248-1474	0-12.5	120
"	"	Tku	Both	110.73	-0.0031	-0.5083	0.36	224-981	3.8-18.3	120
139	Turunväylä	Hki	Basic	114.63	-0.0085	-0.3597	0.50	382-1239	7.9-43.5	120
	"	Hki	Passing	120.91	-0.0020	-0.7215	0.23	64-1313	0-10.6	120
	"	Hki	Both	113.04	-0.0034	-0.2464	0.19	468-2553	6-32.3	120
107	Häm. Väylä	Hki	Basic	85.33	-0.0030	-0.0391	0.14	183-1671	4.8-25.8	80
"	"	Hki	Passing	94.93	-0.0031	-0.1009	0.30	69-1961	0-17.6	80
"	"	Hki	Both	85.11	-0.0001	-0.0378	0.01	183-3633	3.7-23	80
108	Häm. Väylä	Hki	Basic	114.19	-0.0040	-0.2942	0.11	192-873	5.1-37.8	120
"	"	Hki	Passing	124.18	-0.0148	-0.6367	0.14	10-504	0-16.7	120
"	"	Hki	Both	115.19	-0.0016	-0.3129	0.10	206-1359	3.7-29.5	120
137	Häm. Väylä	Hki	Basic	109.27	-0.0048	-0.3052	0.35	182-1339	6.1-30.9	120
"	"	Hki	Passing	118.47	-0.0039	-0.4819	0.32	99-1960	0-10	120
"	"	Hki	Both	110.63	-0.0013	-0.3192	0.22	184-3275	3.8-23.1	120
137	Häm. Väylä	Häm	Basic	116.75	-0.0064	-0.3760	0.58	232-1382	9.4-33.9	120
"	"	Häm	Passing	122.53	-0.0025	-0.4262	0.28	20-2117	0-6.4	120
"	"	Häm	Both	117.92	-0.0026	-0.4175	0.38	189-3499	4.6-31.3	120
109	Lah. Väylä	Hki	Basic	107.30	-0.0065	-0.2158	0.50	540-1868	4.4-31.2	100
"	"	Hki	Passing	113.33	-0.0044	-0.2978	0.51	96-2247	0-9.8	100
"	"	Hki	Both	105.98	-0.0015	-0.2370	0.28	199-4043	3.7-23.1	100
109	Lah. väylä	Lahti	Basic	106.49	-0.0065	-0.1849	0.36	239-1637	6.9-31.6	100
"	"	Lahti	Passing	111.93	-0.0020	-0.0189	0.31	16-1616	0-25	100
"	"	Lahti	Both	105.49	-0.0013	-0.1827	0.15	252-3244	5.6-24.5	100

Table 32. Space mean speed as a function of flow rate and HV% on different freeways. ***Model:*** $V_s = a + b \times q + c \times HV\%$

LAM sites	Location	Dire-ction	Lane type	Intercept a	Coeffic. b	Coeffic. c	R^2	Flow range (veh/h)	Range of HV%	Speed Limit (km/h)
112	Por. Väylä	Hki	Basic	108.86	0.0032	-0.3567	0.50	239-864	4.7-30.6	120
"	"	Hki	Passing	119.81	0.0040	-0.6455	0.32	154-670	0-7	120
"	"	Hki	Both	110.91	0.0038	-0.4204	0.80	272-1470	3.7-23.6	120
131	Tuus. Väylä	Hki	Basic	102.22	-0.0086	-0.1150	0.80	606-1634	4.8-21.1	100
"	"	Hki	Passing	106.88	-0.0049	-0.1561	0.76	206-2010	0-5.5	100
"	"	Hki	Both	99.69	-0.0019	-0.1077	0.57	788-3644	3.6-16.2	100
131	Tuus. Väylä	Tusla	Basic	105.67	-0.0059	-0.3228	0.75	556-1415	0.4-23.6	100
"	"	Tusla	Passing	111.24	-0.0032	-0.6608	0.40	148-1392	0-5.5	100
"	"	Tusla	Both	106.56	-0.0020	-0.4260	0.67	704-2808	4.6-17.7	100

Table 33. Space mean speed as a function of flow rate. The vehicle types were separated with a dummy variable. ***Model:*** $V_s = a + b \times q + c \times D$ *(D = 0 for light vehicles and D = 1 for heavy vehicles)*

LAM sites	Location	Direction	Lane type	Intercept a	Coeffic. b	Coeffic. c	R^2	Flow range (veh/h)	Range of HV%	Speed limit (km/h)
101	Länsiväylä	Hki	Basic	95.34	-0.0098	-2.81	0.14	366-1976	0-22	80
"	"	Hki	Passing	96.60	-0.0045	-4.16	0.38	48-2347	0-10	80
"	"	Hki	Both	93.30	-0.0036	-5.19	0.22	445-4302	0-20	80
"	"	Hki	Bus	90.10	-0.0241	-8.59	0.75	44-486	15-92	80
102	Länsiväylä	Hki	Basic	95.88	-0.0026	-13.41	0.91	224-981	1.8-22	100
"	"	Hki	Passing	106.52	-0.0122	-13.15	0.49	24-493	0-9	100
"	"	Hki	Both	97.09	-0.0031	-15.05	0.92	248-1474	1.5-18.5	100
104	Turunväylä	Tku	Basic	104.55	-0.0011	-18.06	0.92	24-493	0.7-21.8	120
"	"	Tku	Passing	121.44	-0.0036	-19.25	0.82	248-1474	0-12.5	120
"	"	Tku	Both	108.08	-0.0018	-22.51	0.96	224-981	3.8-18.3	120
139	Turunväylä	Hki	Basic	105.27	-0.0005	-18.71	0.91	382-1239	7.9-43.5	120
	"	Hki	Passing	117.76	-0.0020	-16.83	0.63	64-1313	0-10.6	120
	"	Hki	Both	108.32	-0.0008	-22.40	0.95	468-2553	6-32.3	120
107	Häm. väylä	Hki	Basic	88.42	-0.0050	-4.37	0.43	183-1671	4.8-25.8	80
"	"	Hki	Passing	94.09	-0.0019	-4.75	0.15	69-1961	0-17.6	80
"	"	Hki	Both	88.0	-0.0013	-6.08	0.58	183-3633	3.7-23	80
108	Häm. väylä	Hki	Basic	113.89	-0.0029	-24.68	0.87	192-873	5.1-37.8	120
"	"	Hki	Passing	123.97	-0.0163	-26.02	0.59	10-504	0-16.7	120
"	"	Hki	Both	115.65	-0.0020	-26.71	0.86	206-1359	3.7-29.5	120
137	Häm. väylä	Hki	Basic	109.91	-0.0019	-18.71	0.95	182-1339	6.1-30.9	120
"	"	Hki	Passing	120.38	-0.0006	-15.13	0.61	99-1960	0-10	120
"	"	Hki	Both	112.30	-0.0004	-22.59	0.98	184-3275	3.8-23.1	120
137	Häm. väylä	Häm	Basic	109.91	-0.0019	-18.71	0.95	232-1382	9.4-33.9	120
"	"	Häm	Passing	120.38	-0.0006	-15.13	0.61	20-2117	0-6.4	120
"	"	Häm	Both	112.30	-0.0004	-22.60	0.98	189-3499	4.6-31.3	120
109	Lah. väylä	Hki	Basic	102.79	-0.0035	-11.10	0.88	540-1868	4.4-31.2	100
"	"	Hki	Passing	111.86	-0.0022	-10.30	0.53	96-2247	0-9.8	100
"	"	Hki	Both	103.56	-0.0006	-14.01	0.93	199-4043	3.7-23.1	100

Table 34. Space mean speed as a function of flow rate. The vehicle types were separated with a dummy variable. ***Model: V_s = a + b x q + c x D*** *(D = 0 for light vehicles and D = 1 for heavy vehicles)*

LAM sites	Location	Direction	Lane type	Intercept a	Coeffic. b	Coeffic. c	R^2	Flow range (veh/h)	Range of HV%	Speed limit (km/h)
109	Lah. väylä	Lahti	Basic	104.46	-0.0050	-12.69	0.86	239-1637	6.9-31.6	100
"	"	Lahti	Passing	112.45	-0.0023	-10.20	0.53	16-1616	0-25	100
"	"	Lahti	Both	105.36	-0.0013	-15.78	0.92	252-3244	5.6-24.5	100
112	Por. Väylä	Hki	Basic	106.32	0.0052	-22.68	0.97	239-864	4.7-30.6	120
"	"	Hki	Passing	119.90	0.0003	-24.95	0.81	154-670	0-7	120
"	"	Hki	Both	109.15	0.0041	-25.51	0.98	272-1470	3.7-23.6	120
131	Tuus. Väylä	Hki	Basic	98.72	-0.0058	-8.66	0.90	606-1634	4.8-21.1	100
"	"	Hki	Passing	105.60	-0.0032	-6.78	0.56	206-2010	0-5.5	100
"	"	Hki	Both	98.66	-0.0013	-11.95	0.95	788-3644	3.6-16.2	100
131	Tuus. Väylä	Tusla	Basic	98.25	-0.0020	-8.62	0.89	556-1415	0.4-23.6	100
"	"	Tusla	Passing	109.71	-0.0021	-6.66	0.42	148-1392	0-5.5	100
"	"	Tusla	Both	100.04	-0.0003	-12.06	0.95	704-2808	4.6-17.7	100

8.4 Speed distributions on freeways

The cumulative speed distributions on different freeways based on data from the LAM sites are given in *Appendix J*. The speed distribution curves were drawn for the passing lanes and basic lanes separately using data from several LAM sites (LAM 101, 102, 104, 107, 108, 109, 112, 131, 137). A total of 154 hours of point measurement data were used including information of 296,266 vehicles. The data were separated for peak hour traffic and off peak hour traffic.

The speed differences between light and heavy vehicles varied a lot on both basic and passing lanes. In most cases the speed differences between light and heavy vehicles were larger on the basic lane than on the passing lane. In some cases the results were reverse. The speed differences between light and heavy vehicles varied between different measurement points, too, due to different speed limits and flow rates. For example on Länsiväylä the speed differences varied between 0 and 6 km/h on the basic lane, and between 0 and 8 km/h on the passing lane at LAM 101 (speed limit 80 km/h). The corresponding values varied between 0 and 17 km/h on the basic lane and between 0 and 11 km/h on the passing lane at LAM 102 (speed limit 100 km/h). Speed differences between light and heavy vehicles at different speed limit areas are given in *Table 35*.

Table 35. Speed differences between light and heavy vehicles at different speed limit areas.

Speed difference (km/h)	Speed limit 80 km/h	Speed limit 100 km/h	Speed limit 120 km/h
Basic lane	0-20	0-15	0-27
Passing lane	0-10	0-10	0-25

The speed distributions of light and heavy vehicles varied a lot between different LAM sites. To eliminate the variations the speed distribution curves were also drawn by pooling the data from all LAM sites with the same speed limit.

On road sections where speed limit was 80 km/h the speed of the light vehicles varied between 60 and 110 km/h and of the heavy vehicles between 40 and 110 km/h on the basic lanes. The mode was around 90 km/h. On the passing lanes the speeds of the light vehicles varied between 50 and 140 km/h and of the heavy vehicles between 40 and 110 km/h. The mode was just over 80 km/h. The cumulative distributions of speeds for light and heavy vehicles on the sections with speed limit 80 km/h are given in *Figures 58-59.*

On the sections with speed limit 100 km/h the speeds of the light vehicles varied between 70 and 140 km/h and of the heavy vehicles between 60 and 120 km/h on basic lanes. The mode of the speed of the light vehicles was around 100 km/h and of the heavy vehicles just over 90 km/h. On passing lanes the speeds of the light vehicles fluctuated between 80 and 140 km/h and of the heavy vehicles between 60 and 120 km/h. The mode of the speeds of the light vehicles was around 110 km/h and of the heavy vehicles around 100 km/h. The cumulative distributions of speeds for light and heavy vehicles on the 100 km/h speed limit sections are given in *Figures 60-61*.

On the sections with speed limit 120 km/h the overall speeds of the light vehicles fluctuated between 80 and 140 km/h and of the heavy vehicles between 60 and 110 km/h on basic lanes. The mode of the speeds of the light vehicles was 120 km/h and of the heavy vehicles 90 km/h. On passing lanes the speeds of the light vehicles fluctuated between 90 and 150 km/h and of the heavy vehicles between 60 and 120 km/h. The mode of the speeds of the light vehicles was around 130 km/h and of the heavy vehicles around 100 km/h. The cumulative speed distributions are given in *Figures 62-63*.

The speed differences of the light vehicles between peak hours and off peak hours varied between 0 and 8 km/h. The variations of speed of the heavy vehicles between peak hours and off peak hours are hardly noticeable.

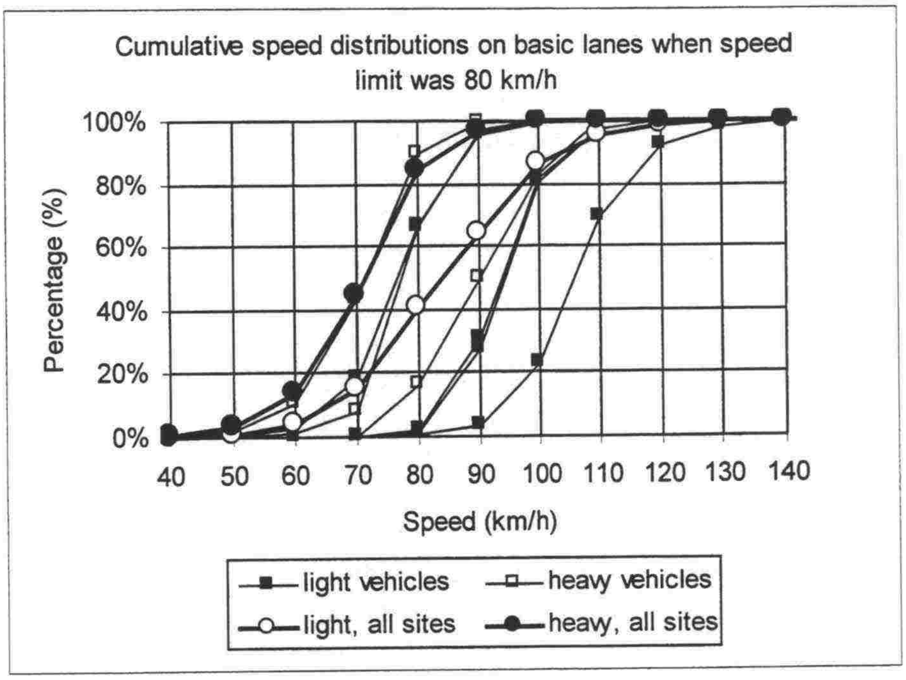

Figure 58. Cumulative speed distributions on the basic lanes, at LAM sites where speed limit was 80 km/h. The bolded curves were drawn by pooling the data from all LAM sites on 80 km/h speed limit sections.

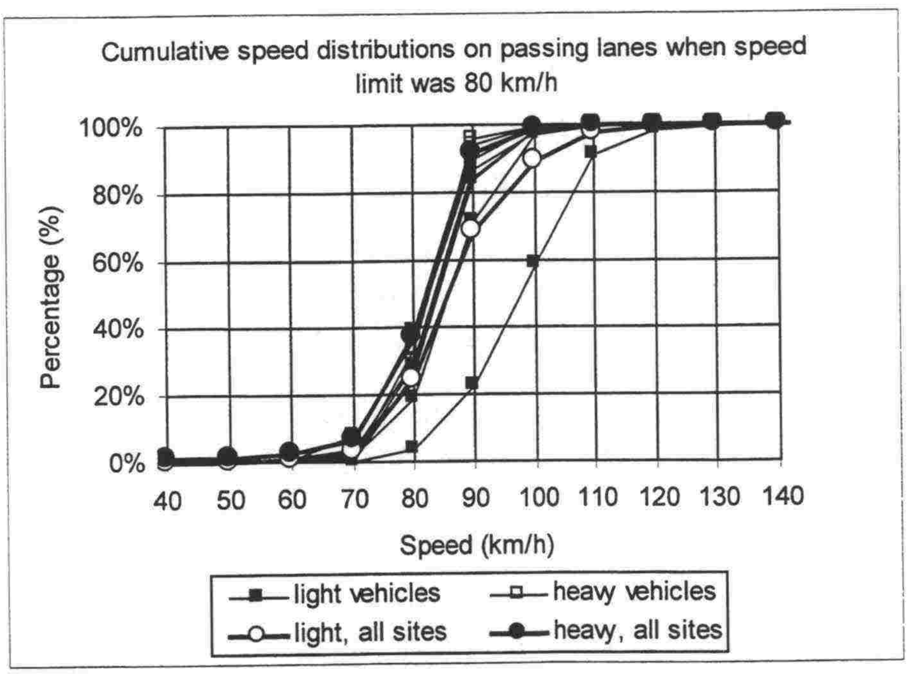

Figure 59. Cumulative speed distributions on the passing lanes where speed limit was 80 km/h. The bolded curves were drawn by pooling the data from all LAM sites on 80 km/h speed limit sections.

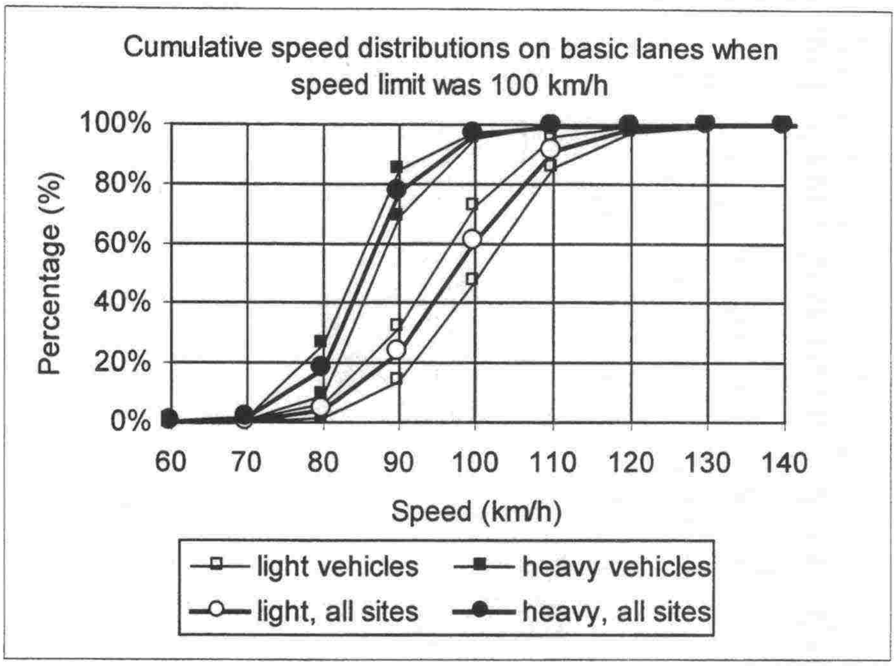

Figure 60. Cumulative speed distributions on the basic lanes where speed limit was 100 km/h. The bolded curves were drawn by pooling the data from all LAM sites on 100 km/h speed limit sections.

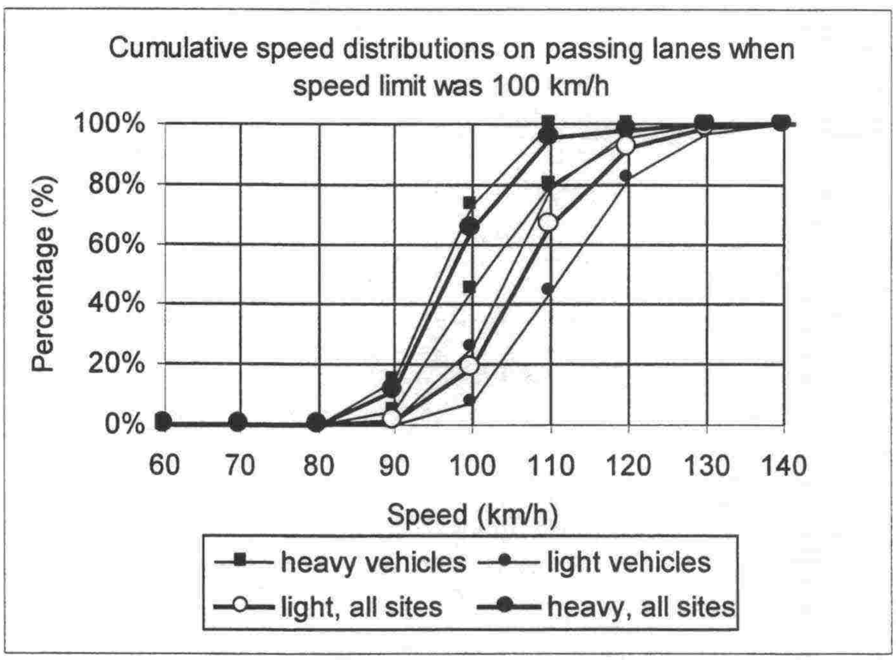

Figure 61. Cumulative speed distributions on the passing lanes where speed limit was 100 km/h. The bolded curves were drawn by pooling the data from all LAM sites on 100 km/h speed limit sections.

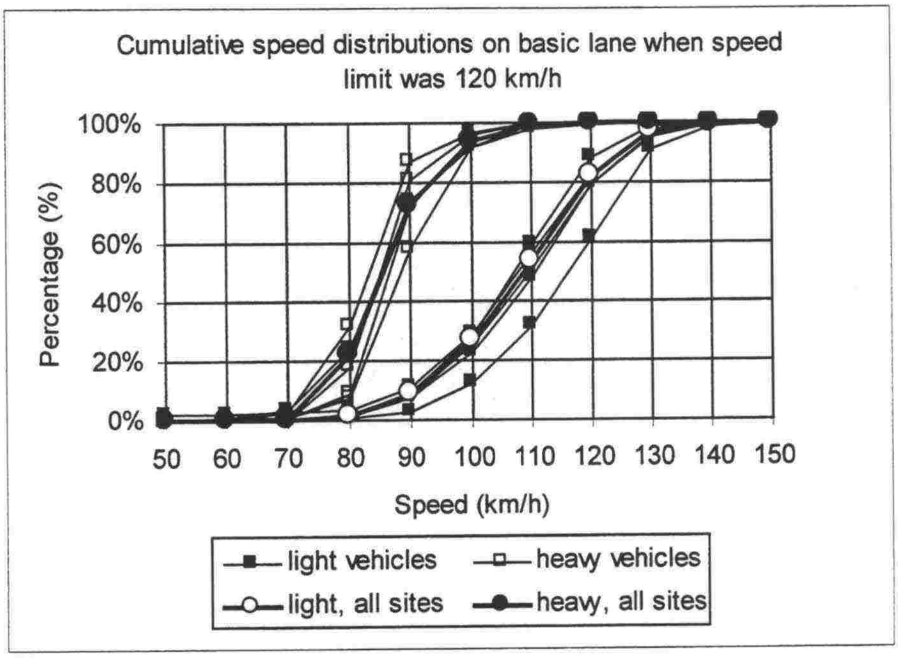

Figure 62. Cumulative speed distributions on the basic lanes where speed limit was 120 km/h. The bolded curves were drawn by pooling the data from all LAM sites on 120 km/h speed limit sections.

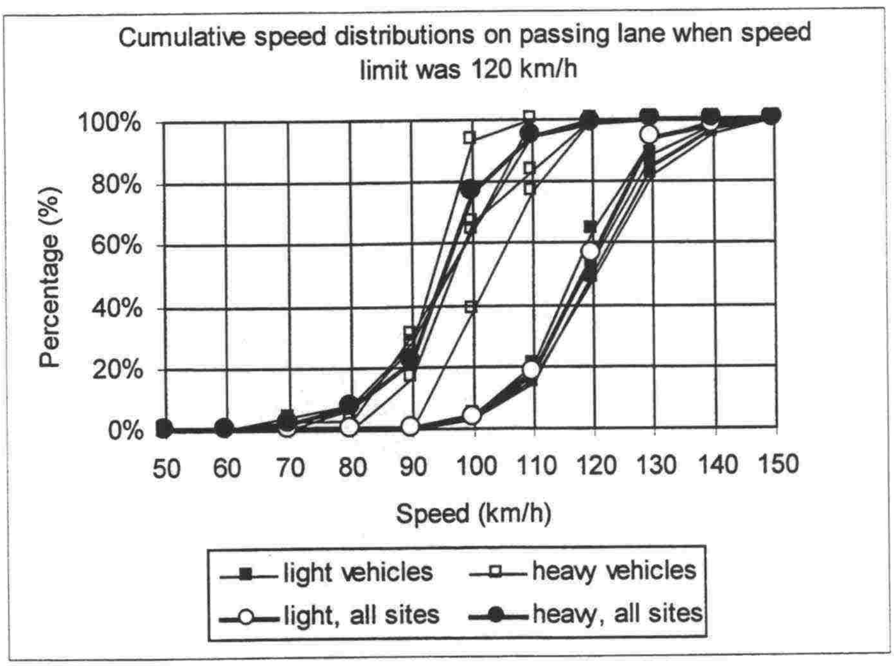

Figure 63. Cumulative speed distributions on the passing lanes where speed limit was 120 km/h. The bolded curves were drawn by pooling the data from all LAM sites on 120 km/h speed limit sections.

9 EFFECT OF ROAD GEOMETRY ON SPEED

9.1 General

To evaluate the effect of any geometric feature, some traffic variables have to be measured and compared for different geometric variables. In the case of freeway sections and entrance ramps, the speed of different vehicle types is such a variable and assumed to describe the operating conditions encountered at different types of design. The effect of heavy vehicles on traffic flow characteristics has long been a subject of interest to traffic engineering. The basic method for capturing the effect of heavy vehicles compared to that of passenger cars has been the passenger car equivalent (PCE) concept, which is widely adopted in the Highway Capacity Manual (HCM 1994).

The objective of this section is to investigate and quantify the effect of traffic volume on the average travel speed on ramps and grades with specific attention given to the geometry of the road section. The operational characteristics of light vehicles and heavy vehicles are ascertained and compared for different geometric features. This is because it is well known that there is a significant relationship between the travel speed of the heavy vehicles and the gradient of the roads. Some of heavy vehicles are able to maintain speeds equal or close to the speed of the passenger cars only on level terrain where speed limit is 80 km/h. On upgrades the speed of the heavy vehicles may vary widely depending on steepness and length of the grade (see section 7.4). It is obvious that trucks with their loads travel at slower speed on upgrades than on level sections.

9.2 Geometrical effects on ramp speeds

The methodological approach following in this section is similar to that used in earlier sections. Essentially, multivariate regression analyses are used to explain the relationship between average travel speed, flow rate, grade and radius of the ramps (*Equations 63-64*). The models given below are estimated by pooling the data from all ramps. The 5-minute flow rates varied between 24 and 732 veh/h. The hilliness varied between 17 and 28 m/km, and the radii of the curves included in the models varied between 50 and 180 m.

$$V_{light} = 64.61 - 0.02276\,Q - 0.6108\,H + 0.1559\,R \qquad R^2 = 0.65 \quad (63)$$

$$V_{heavy} = 41.83 - 0.0224\,Q - 0.1523\,H + 0.2003\,R \qquad R^2 = 0.61 \quad (64)$$

where:

v = average travel speed (km/h)
Q = flow rate (veh/h)
H = hilliness (m/km)
R = radii of curve ramps (m).

The average travel speed on a ramp increases as the radius of the ramp increases. On the other hand average travel speed decreases when the hilliness of the ramps increases for both light and heavy vehicles. Travel speed as a function of curves' radii and hilliness of ramps is given in *Table 36.*

Table 36. Travel speed as a function of curves' radii and hilliness of ramps.

Average speed (km/h)	Intercept (a)	Coefficient (b)	R^2	Range of hilliness and radii
V_{light}	92.38	-1.3914	0.55	17-28 (m/km)
V_{heavy}	79.47	-1.1115	0.35	17-28 (m/km)
V_{light}	50.01	0.1127	0.30	50-180 (m)
V_{heavy}	36.18	0.1577	0.45	50-180 (m)

It was also noticed that standard deviation of speed on small radius and steep grade ramps was much higher compared to ramps with large radius and gentle grade. The relationships between average travel speed, grade, and radius of the ramp are shown in *Figure 64*. The speed difference between light and heavy vehicles was about two times higher on ramps with low radius than on ramps with high radius. The speed difference between light and heavy vehicles was about 10 km/h on ramps with hilliness 10 m/km, whereas this difference was only about 5 km/h on ramps with hilliness 30 m/km. This means that speeds of the heavy vehicles are affected faster by changes in grade and radius of ramps than speeds of light vehicles. Generally trucks need more time to join the ramp stream from the main stream, and thus the speeds are reduced. On the other hand, their acceleration rate is lower than that of passenger cars which causes lower average speeds.

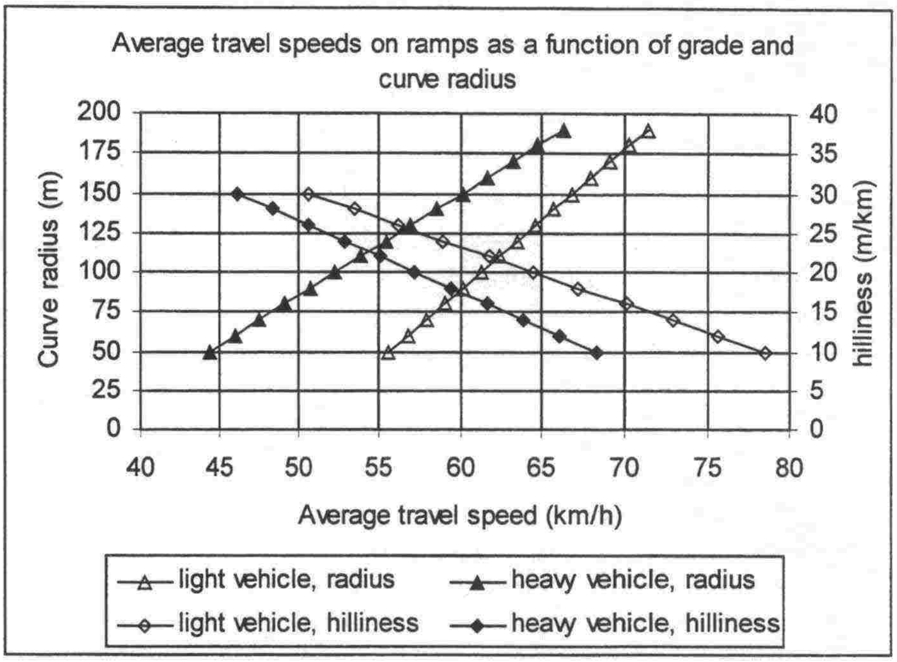

Figure 64. Average travel speeds on ramp as a function of hilliness and curves' radii.

9.3 Geometrical effects on upgrade and downgrade speeds

The relationship between the average travel speeds, flow rate, and hilliness of the grade (m/km) has been established with linear regression. A dummy variable was included for separating the speeds of light and heavy vehicles. The regression models were developed for upgrades and downgrades separately and they are given below:

$$V_{upgrade} = 122.22 - 0.0231\,Q - 16.63\,D - 0.3066\,H \qquad R^2 = 0.81 \quad (65)$$

$$V_{downgrade} = 120.15 - 0.0045\,Q - 17.43\,D - 0.4272\,H \qquad R^2 = 0.81 \quad (66)$$

where:

V = average travel speed (km/h)
Q = flow rate (veh/h)
H = hilliness (m/km)
D = dummy variable, 0 when light vehicle and 1 when heavy vehicle

Data from all measurement sites together were used for the models. The lengths of the grades varied from 1.1 km to 3.4 km. The speed limit was 80 km/h on one grade and 120 km/h on the other two. The speed difference between light and heavy vehicles was about 17 km/h. The speed reduction because of flow rate was faster on upgrades than on downgrades. The speeds of the heavy vehicles did not vary very much with different speed limits but the speeds of the light vehicles varied a lot with different speed limits. The speed differences between light and heavy vehicles were much higher on sections where the grade was steep than on sections where the grade was not steep.

Obviously not only drivers of heavy vehicles react to the hilliness, drivers of light vehicles react to the local hilliness as well. The standard deviation of speed on level sections is lower compared to the standard deviation of speed on a grade. On road sections where the hilliness is very low the speeds of the vehicles do not vary very much. Therefore this greater speed variation with the hilliness of the road section can in general be ascribed to a behavioural response, but for heavy vehicles it can also be attributed to a difference in acceleration and braking capabilities. The relationship between average travel speed and hilliness is illustrated in *Figure 65.*

Figure 65 is drawn using the equations given below:

$$V_{upgrade} = 108.6 - 16.63\ D - 0.4028\ H \qquad R^2 = 0.75 \quad (67)$$

$$V_{downgrade} = 114.8 - 17.43\ D - 0.4123\ H \qquad R^2 = 0.81 \quad (68)$$

The descriptions of the parameters are the same as in *Equations (65) and (66).*

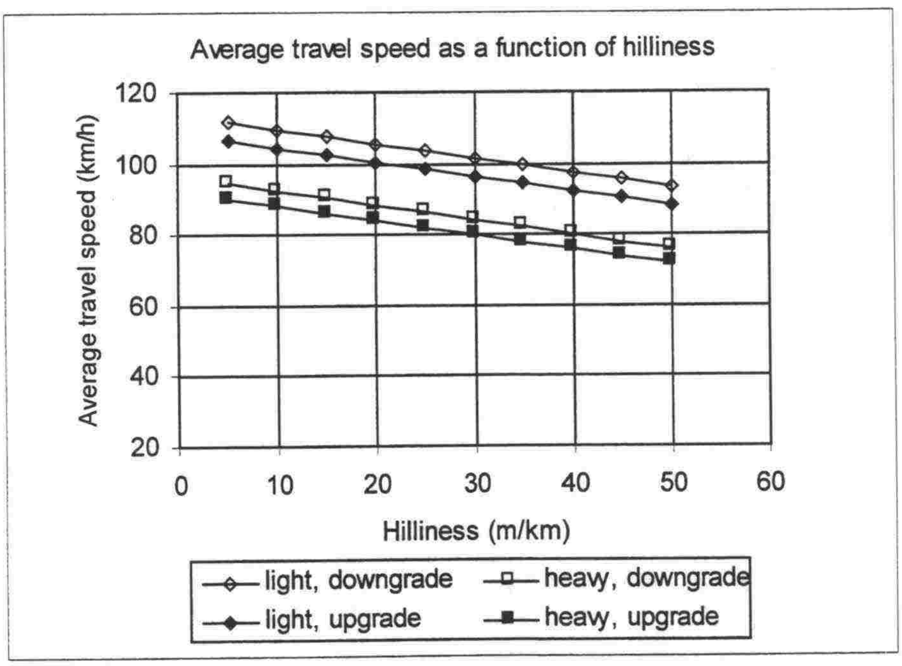

Figure 65. Average travel speed as a function of hilliness.

10 PLATOONING

10.1 General

To determine the quality of traffic operations it is important to know the level of platooning on the road type in question. Platooning is of particular importance on two-lane two-way highways but it can also be used as a measure of quality of freeway flow. In this study a vehicle is considered to belong to a platoon when its time headway is less than or equal to 5 seconds. Regardless of road type some vehicles are always obliged to follow the vehicle in front because of the lack of overtaking possibilities. The analysis of platooning has been made using log-linear regression, which is based on assumptions of negative exponential headway distributions and geometric platoon length distributions (Pursula & Enberg 1991). The point measurement data gathered from the LAM sites were used for the platooning analyses.

10.2 Platoon percentages and flow rates

With linear regression the relationship between platoon percentage (P, %), flow rate (Q, veh/h), and proportion of heavy vehicles (HV%) has been established. The model given below is estimated using 15-minute average of flow rate, platoon percentage, and heavy vehicle percentage.

The log-linear regression curve for platoon percentage as a function of flow rate and HV% has the form

$$\ln (100-p) = a + b \times Q + c \times HV\% \qquad (69)$$

The equation parameters a, b and c are given in *Tables 37-38*. On sections where the speed limit was 80 km/h the range of the 15-minute average platoon percentages on the basic lanes was 28-99 and 5-98% on the passing lanes. The impact of the flow rate and heavy vehicles on platooning was sometime higher on basic lane and sometime higher on passing lane. In most cases the coefficients of flow rate and heavy vehicles have higher value on basic lane than on passing lane. *Tables 37-38* show clear differences between the data collection points and between the basic lanes and the passing lanes, even if the speed limit was the same. The platoon percentages as a function of flow rate for average proportions of heavy vehicles on both lanes are given in *Figures 66-67*. The curves in *Figure 66* show that the differences in platoon percentages at low flow areas on the basic lanes between different LAM sites were quite high. The reason might be different average proportion heavy vehicles in different LAM sites. At high flow areas the differences in platoon percentages were quite small as a whole. The curves in *Figure 67* show that the differences in platoon percentages on the passing lanes between different LAM sites also were quite small for all flow conditions. The differences occur partly because of road conditions and partly because of traffic compositions.

On sections where the speed limit was 100 km/h the range of the 15-minute average platoon percentages on the basic lanes was 52-98, and on the passing lanes 13-97%. In *Figures 68-69* the negative exponential relationships between platoon percentage and flow rate for average proportion of heavy vehicles are presented. The curves show that the differences in platooning on the basic lanes and passing lanes between the measurement locations were very small as a whole. The platoon percentages were smaller at low flow areas (500 veh/h) on the basic lanes than on the passing lanes but were larger at high flow areas (1500 veh/h) on the basic lanes than on the passing lanes.

On sections where the speed limit was 120 km/h the platoon percentages were a little lower than on other speed limit sections (80 km/h, 100 km/h). The range of the 15-minute average platoon percentages on the basic lanes was 14-88 and 4-95% on the passing lanes. The regression coefficients for flow rate and for heavy vehicles were on the same level as or, in some cases, slightly smaller than on sections with speed limit 80 or 100 km/h. In *Figures 70-71*, the relationships between platoon percentages and flow rate for average proportion of heavy vehicles are presented. The figures show that the percentages of vehicles in platoons were clearly higher on basic lanes than passing lanes. At high flow areas the platoon percentages on basic lanes were on the same level as on passing lanes. The differences in platooning on the basic and passing lanes between the measurement locations were quite small as a whole.

The impact of heavy vehicles on platooning was sometimes higher on the basic lanes and sometimes higher on the passing lanes. The overall platooning increased as the proportions of heavy vehicles increased. The impact of flow rates on platooning is faster than the impact of heavy vehicles. The overall platoon percentages were higher for low speed limits than for high speed limits. The platoon percentage was higher on the basic lanes than on the passing lanes and it increased as the flow rate increased.

Table 37. Platoon percentage (p, %) as a function of flow rate (q, veh/h) and heavy vehicles (HV%). ***Model: ln (100-p) = a + b x q + c x HV%***

LAM sites	Locations	Dire-ction	Lane type	Inter-cept a	Coeffic. b	Coeffic. c	R^2	Flow range (veh/h)	Range of HV%	Speed limit (km/h)
101	Länsiväylä	Hki	Basic	5.22	-0.0022	-0.0091	0.90	366-1976	0-22	80
"	"	Hki	Passing	4.48	-0.0015	-0.0024	0.96	48-2347	0-10	80
"	"	Hki	Bus	4.44	-0.0012	-0.0023	0.64	44-486	15-92	80
102	Länsiväylä	Hki	Basic	4.65	-0.0016	-0.0004	0.93	224-981	1.8-22	100
"	"	Hki	Passing	4.47	-0.0019	-0.0088	0.69	24-493	0-9	100
104	Turunväylä	Tku	Basic	4.83	-0.0017	-0.0007	0.97	210-960	0.7-21.8	120
"	"	Tku	Passing	4.48	-0.0015	-0.0023	0.98	20-912	0-12.5	120
139	Turunväylä	Hki	Basic	4.85	-0.0018	-0.0031	0.97	382-1239	7.9-43.4	120
"	"	Hki	Passing	4.43	-0.0014	-0.0023	0.94	64-1313	0-10.6	120
107	Häm.väylä	Hki	Basic	4.21	-0.0012	-0.0043	0.41	183-1671	4.8-25.8	80
"	"	Hki	Passing	4.48	-0.0014	-0.0018	0.98	69-1961	0-17.6	80
108	Häm.väylä	Hki	Basic	4.71	-0.0015	-0.0005	0.92	192-873	5.1-37.8	120
"	"	Hki	Passing	4.51	-0.0017	-0.0006	0.72	10-504	0-16.7	120
137	Häm.väylä	Häm	Basic	4.87	-0.0019	-0.0034	0.96	232-1382	9.4-33.9	120
"	"	Häm	Passing	4.42	-0.0013	-0.0010	0.95	20-2117	0-6.4	120
137	Häm.väylä	Hki	Basic	4.83	-0.0018	-0.0023	0.95	182-1339	6.1-30.9	120
"	"	Hki	Passing	4.41	-0.0014	-0.0005	0.98	99-1960	0-10	120
109	Lah.väylä	Hki	Basic	5.12	-0.0022	-0.0030	0.98	540-1848	4.4-31.2	100
"	"	Hki	Passing	4.44	-0.0014	-0.0006	0.97	96-2247	0-9.8	100
109	Lah.väylä	Lahti	Basic	4.93	-0.0019	-0.0004	0.97	239-1637	6.9-31.6	100
"	"	Lahti	Passing	4.40	-0.0013	-0.0022	0.96	16-1616	0-25	100

Table 38. Platoon percentage (p, %) as a function of flow rate (q, veh/h) and heavy vehicles (HV%). ***Model: ln (100-p) = a + b x q + c x HV%***

LAM sites	Locations	Dire-ction	Lane type	Inter-cept a	Coeffic. b	Coeffic. c	R^2	Flow range (veh/h)	Range of HV%	Speed limit (km/h)
112	Por.väylä	Hki	Basic	4.76	-0.0016	-0.0008	0.91	239-864	4.7-30.6	120
"	"	Hki	Passing	4.45	-0.0016	-0.0104	0.77	154-670	0-7	120
131	Tus. Väylä	Hki	Basic	5.04	-0.0020	-0.0044	0.96	606-1634	4.8-21.1	100
"	"	Hki	Passing	4.35	-0.0013	-0.0207	0.98	206-2010	0-5.5	100
131	Tus. Väylä	Tusla	Basic	4.83	-0.0019	-0.0053	0.94	556-1415	0.4-23.6	100
"	"	Tusla	Passing	4.21	-0.0013	-0.0106	0.92	148-1392	0-5.5	100
128	Ring III	Vantaa	Basic	4.71	-0.0018	-0.0051	0.72	132-1289	8-32	80
"	"	Vantaa	Passing	4.61	-0.0019	$-1.4\ 10^{-5}$	0.89	148-1529	0-18	80
128	Ring III	Knummi	Basic	4.38	-0.0016	-0.0051	0.85	416-1382	8-35	80
"	"	Knummi	Passing	4.09	-0.0017	-0.0014	0.92	116-1540	1-24	80

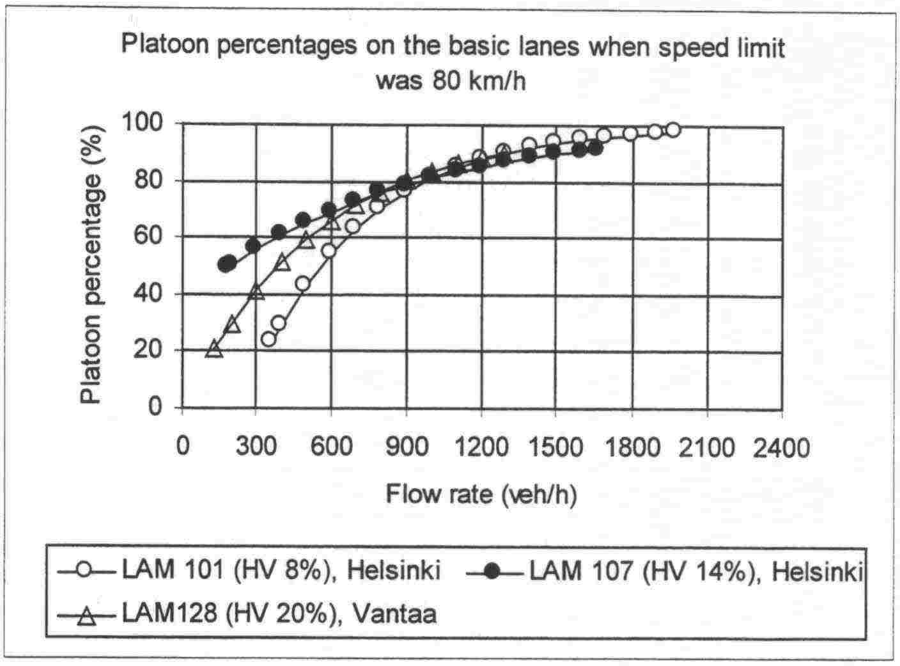

Figure 66. The relationship between platoon percentages and flow rate for average proportion of heavy vehicles on the basic lanes when speed limit was 80 km/h.

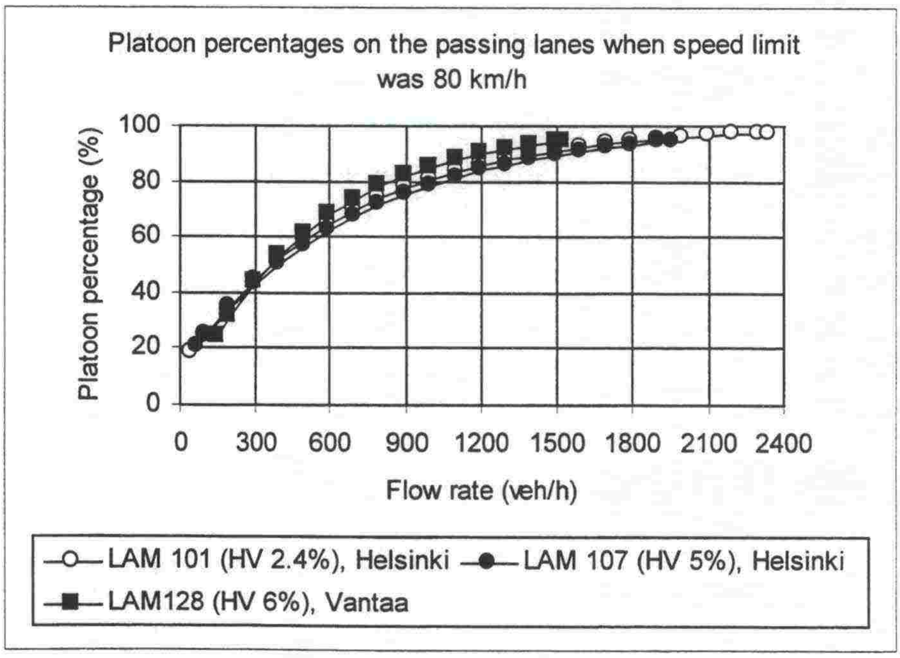

Figure 67. The relationship between platoon percentages and flow rate for average proportion of heavy vehicles on the passing lanes when speed limit was 80 km/h.

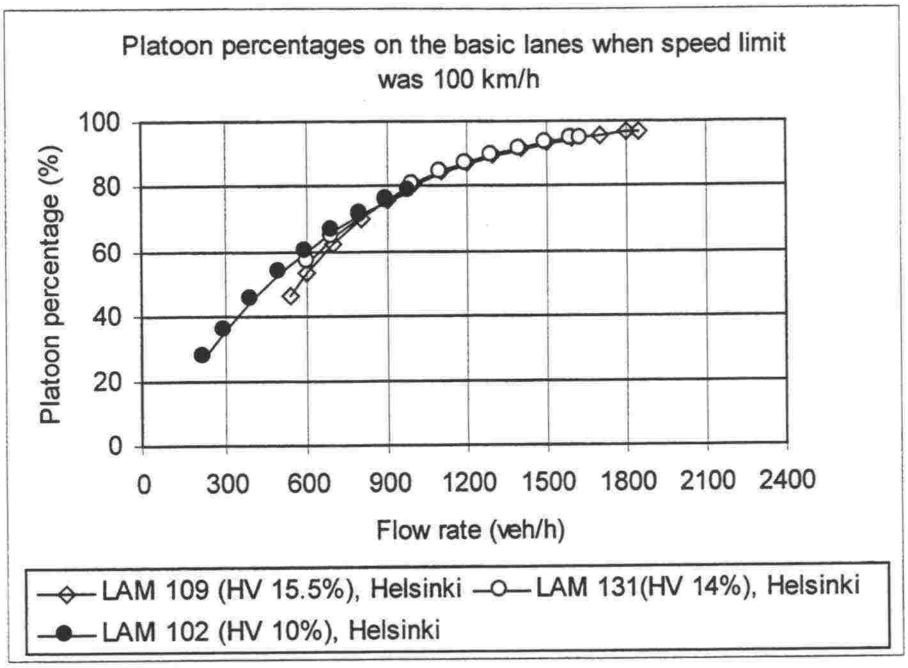

Figure 68. The relationship between platoon percentages and flow rate for average proportion of heavy vehicles on the basic lanes when speed limit was 100 km/h.

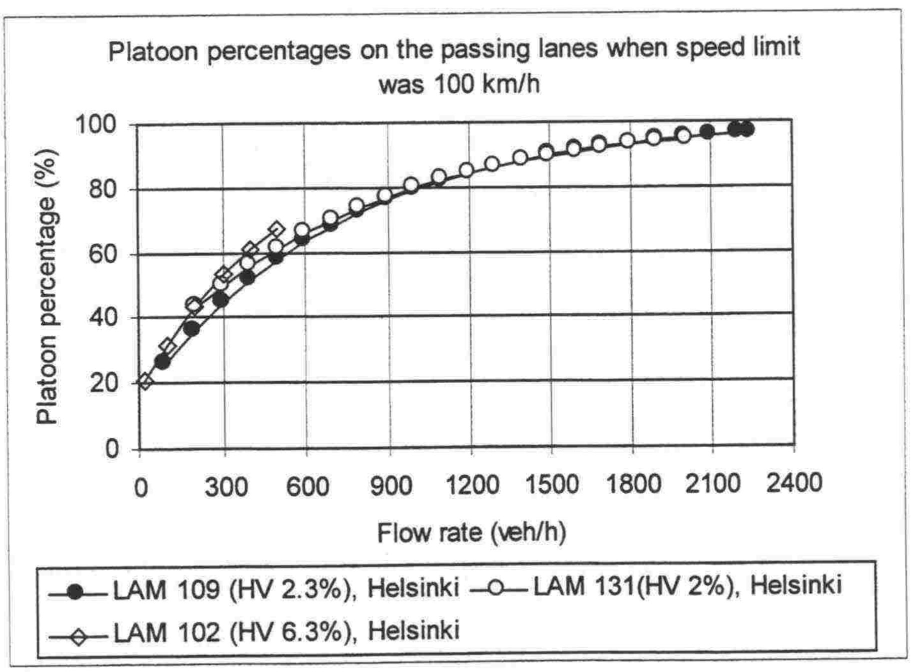

Figure 69. The relationship between platoon percentages and flow rate for average proportion of heavy vehicles on the passing lanes when speed limit was 100 km/h.

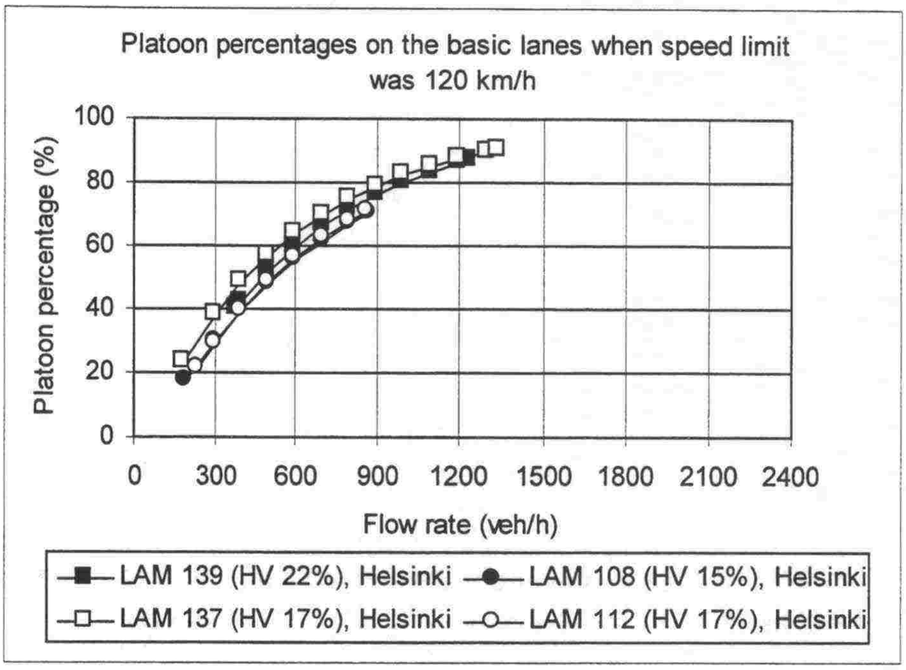

Figure 70. The relationship between platoon percentages and flow rate for average proportion of heavy vehicles on the basic lanes when speed limit was 120 km/h.

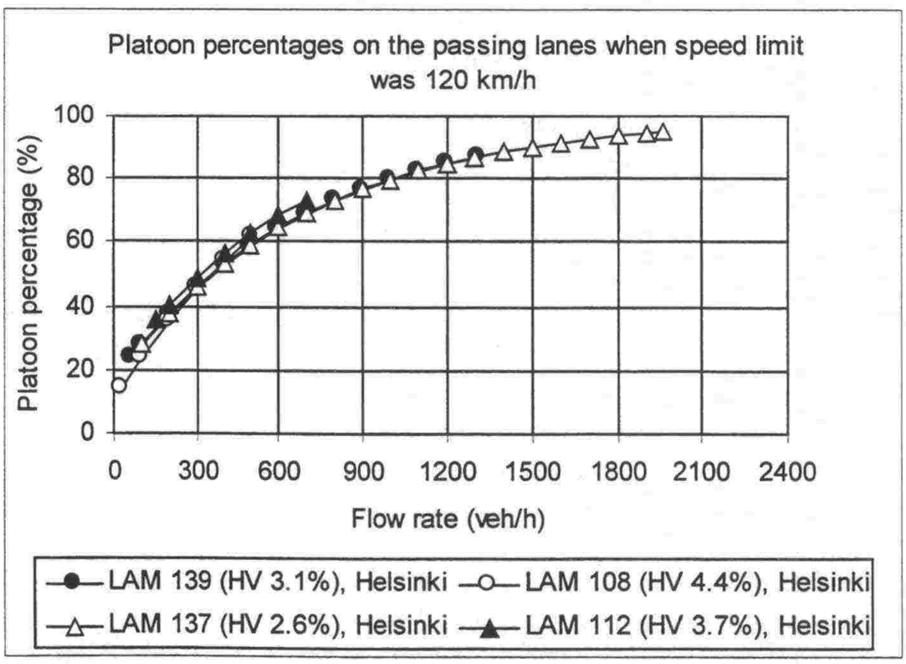

Figure 71. The relationship between platoon percentages and flow rate for average proportion of heavy vehicles on the passing lanes when speed limit was 120 km/h.

10.3 Followers and leaders in platoons

The vehicles in the traffic stream were divided into two types, namely followers and leaders. This was because it is a suitable measure to identify the impact of different vehicle types on platoon formation. On the other hand, the investigation of platoon leaders estimates the propensity for a vehicle type to become a platoon leader. Consequently the number of followers provide a measure of how many vehicles are held up in platoons by the presence of a slow vehicle in the traffic stream.

The type of the platoon leader is an important factor when quantifying the impact of different vehicle types on platoon formation. Generally platoons are formed when fast vehicles catch up slower vehicles without possibility to overtake. Heavy vehicles often have lower desired speeds and poorer acceleration capabilities than standard passenger cars and are more likely to be caught up by faster vehicles. Therefore it is obvious that heavy vehicles have a higher individual propensity to become platoon leaders than passenger cars. The proportions of heavy vehicles that are platoon leaders as a function of percentages of heavy vehicles in the traffic stream are illustrated in *Figures 72-74*. The regression lines shown in *Figures 72-74* were drawn using the data set of basic lane and passing lane together.

According to the data the proportion of light vehicles leading a platoon was lower than the proportion of light vehicles in the traffic stream. The percentage of platoon leaders that were heavy vehicles increased as the percentage of heavy vehicles increased in traffic stream. The percentage of heavy vehicles leading platoons was greater than the percentage of these vehicles in the traffic stream. Heavy vehicles had higher propensity to become a platoon leader on the road sections where the speed limit was 80 km/h than on the road sections where the speed limit was 120 km/h.

On road sections where the speed limit was 80 km/h about 31% of the heavy vehicles were leaders even if they were only 20% of the traffic stream on the basic lane. On the passing lane about 8% of the heavy vehicles were leaders even if they were only 6% of the traffic stream.

On road sections where the speed limit was 100 km/h about 21% of the heavy vehicles were leaders although they were only 15.5% of the traffic stream on the basic lane. On the passing lane about 4% of the heavy vehicles were leaders even if they were only 2.3% of the traffic stream.

On road sections where the speed limit was 120 km/h about 19% of the heavy vehicles were leaders although they were only 17% of the traffic stream on the basic lanes. On the passing lanes about 4% of the heavy vehicles were leaders even if they were only 3% of the traffic stream.

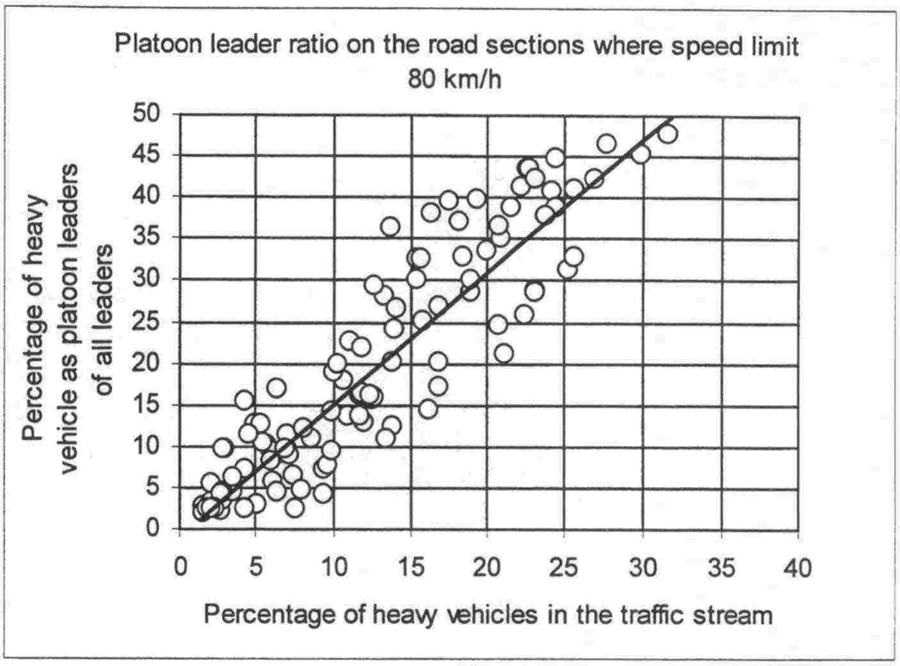

Figure 72. Percentage of heavy platoon leaders as a function of percentage of heavy vehicles in traffic stream when speed limit was 80 km/h.

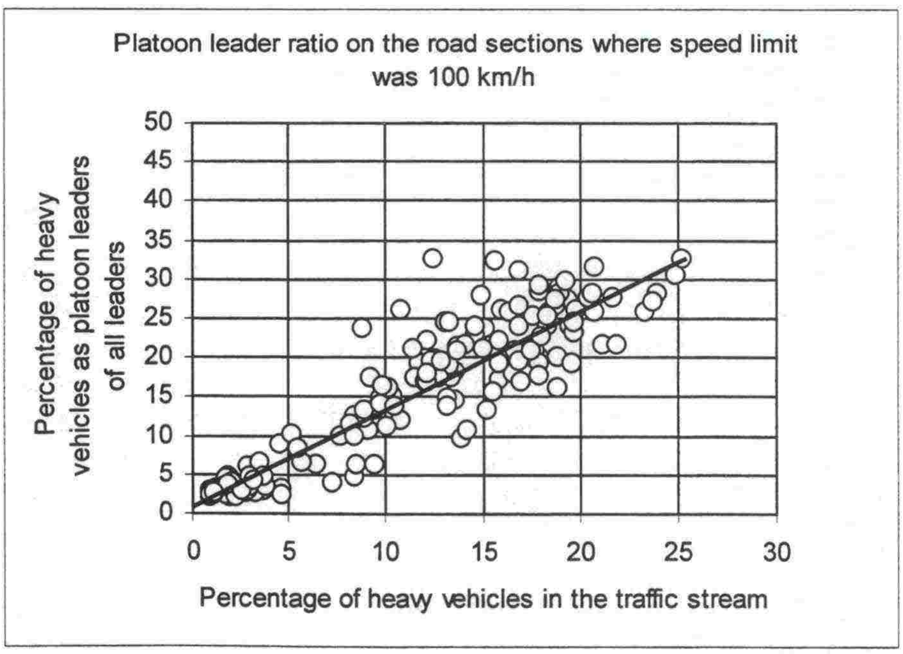

Figure 73. Percentage of heavy platoon leaders as a function of percentage of heavy vehicles in traffic stream when speed limit was 100 km/h.

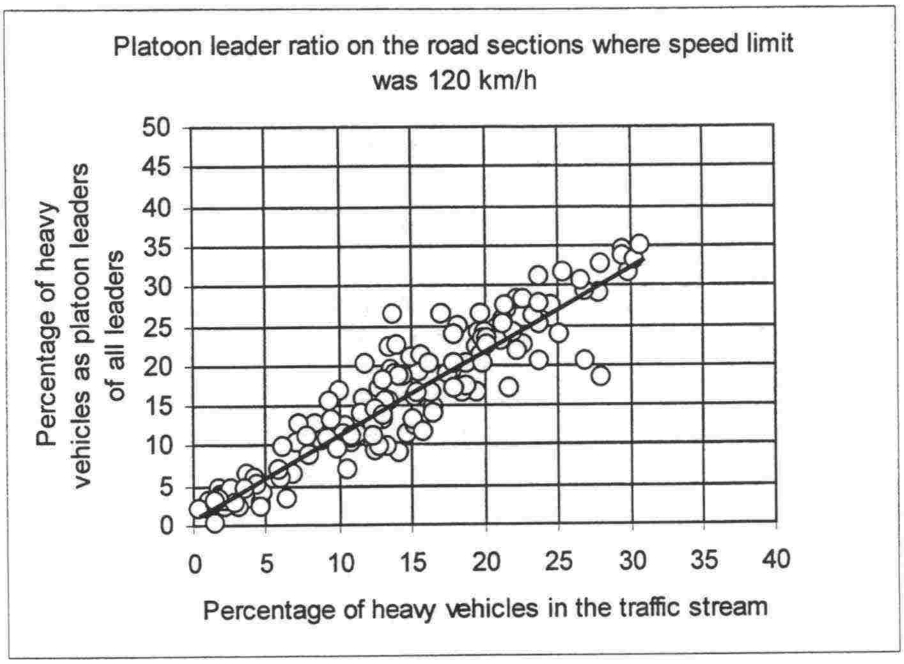

Figure 74. Percentage of heavy platoon leaders as a function of percentage of heavy vehicles in traffic stream when speed limit was 120 km/h.

10.4 Platoon lengths and flow rates

The flow rate and the proportion of heavy vehicles have a direct impact on platoon lengths. With log-linear regression the relationship between the mean platoon length (E(q), vehicle), flow rate (q, veh/h), and proportion of heavy vehicles (HV%) has been established. The log-linear regression equations for mean platoon length (E(q)) as a function of flow rate (q) and proportion of heavy vehicles (HV%) have the form

$$\ln (E(q)) = a + b \times q + c \times HV\% \qquad (70)$$

The equation parameters a, b and c are given in *Tables 39-40.*

On basic lanes when speed limit was 80 km/h about 23% of the platoons consisted of 4 vehicles and 17% of the platoons consisted of 5 vehicles. About 14% of the platoons consisted of 2-3 vehicles. The mode of the frequency of the platoon length distribution was just over 4 vehicles. On passing lanes about 38% of the platoons consisted of 2 vehicles and about 31% of the platoons consisted of 3 vehicles. Only 10% of the platoons consisted of 4 vehicles. The platoon length distributions on basic lanes and passing lanes are given in *Figure 75.* In *Figures 78-79* the corresponding curves of mean platoon length versus one-way flow rate with average proportion of heavy vehicles are presented. Based on the curves it can be stated that there are noticeable differences in mean platoon lengths between different data collection sites and also between the basic lanes and passing lanes, even if the speed limit is the same (80 km/h). The mean platoon lengths were clearly shorter on the passing lanes than on the basic lanes. The differences between different measurement sites were negligible at low flow areas but noticeable at high flow areas. The overall mean platoon length increased as flow rate increased. The mean platoon length also increased as the proportion of heavy vehicles increased.

On sections where the speed limit was 100 km/h the 15-minute mean platoon lengths varied between 2 and 20 vehicles on the basic lanes and between 1 and 18 vehicles on the passing lanes. On basic lanes about 29% of the platoons consisted of 3 vehicles and 27% consisted of 4 vehicles. Only 6% consisted of 2 vehicles. On passing lanes the platoons with 4 vehicles were about 44% and the platoons with 3 vehicles about 29%. Only 4% of the platoons consisted of 1 vehicle. The platoon length distributions on basic lanes and passing lanes are given in *Figure 76*. The exponential relationships between mean platoon length and flow rate with average proportion of heavy vehicles are presented in *Figures 80-81*. No noticeable differences in mean platoon lengths between the measurement sites could be found. Small differences were found only at high flow areas. The mean platoon length on the basic lanes was a little shorter than on the passing lanes. At low flow areas the mean platoon lengths usually were very short. This was because most motorists were able to overtake the impeding vehicle immediately.

On sections where the speed limit was 120 km/h the 15-minute mean platoon lengths varied between 1 and 9 vehicles on the basic lanes and between 1 and 16 vehicles on the passing lanes. On basic lanes the platoons with 2 vehicles were about 60% and the platoons with 3 vehicles were bout 24% of all platoons. Only 5% of the platoons consisted of 4 vehicles. On passing lanes about 19% of the platoons consisted of 1 vehicle and 57% of the platoons consisted of 2 vehicles. The platoons with 3 vehicles were about 14% and only 4% of the platoons consisted of 4 vehicles. The platoon length distributions on basic lanes and passing lanes are given in *Figure 77.* The relationships between mean platoon length and flow rate with average proportion of heavy vehicles are presented in *Figures 82-83.* The curves show that the differences in platoon lengths on the basic and passing lanes between different measurement sites were very small as a whole. Mean platoon length increased as flow rate increased. The mean platoon lengths on the passing lanes were at the same level as on the basic lane.

The overall mean platoon lengths on high speed limit sections (120 km/h) were clearly shorter compared to mean platoon lengths on lower speed sections limit (80-100 km/h). The impact of flow rate and heavy vehicles on platoon lengths was faster on low speed limit sections than on high speed limit sections.

The impact of flow rates on platoon length is faster than the impact of heavy vehicles. The overall mean platoon lengths on low flow areas were clearly shorter compared to mean platoon lengths on high flow areas. Similarly, the mean platoon length was shorter when the proportion of heavy vehicles was lower and longer when the proportion of heavy vehicles was higher.

Table 39. Mean platoon length as a function of flow rate (q, veh/h) and heavy vehicles (HV%) on different roads. ***Model: ln (E(q)) = a + b x q + c x HV%***

LAM sites	Locations	Dire-ction	Lane type	inter-cept a	coeffic. b	coeffic. c	R^2	Flow range (veh/h)	Range of HV%	Speed limit (km/h)
101	Länsiväylä	Hki	Basic	-0.56	0.0022	0.0091	0.89	366-1976	0-22	80
"	"	Hki	Passing	0.20	0.0015	0.0064	0.91	48-2347	0-10	80
"	"	Hki	Bus	0.28	0.0011	0.1063	0.22	44-486	15-92	80
102	Länsiväylä	Hki	Basic	0.04	0.0015	0.0033	0.78	224-981	1.8-22	100
"	"	Hki	Passing	0.42	0.0009	0.0140	0.16	24-493	0-9	100
104	Turunväylä	Tku	Basic	-0.31	0.0017	0.0022	0.95	210-960	0.7-21.8	120
"	"	Tku	Passing	0.17	0.0016	0.0314	0.94	20-912	0-12.5	120
139	Turunväylä	Hki	Basic	-0.14	0.0017	0.0040	0.93	382-1239	7.9-43.4	120
"	"	Hki	Passing	0.25	0.0014	0.0008	0.83	64-1313	0-10.6	120
107	Häm.väylä	Hki	Basic	0.42	0.0012	0.0043	0.40	183-1671	4.8-25.8	80
"	"	Hki	Passing	0.20	0.0014	0.0026	0.93	69-1961	0-17.6	80
108	Häm.väylä	Hki	Basic	-0.09	0.0015	0.0021	0.75	192-873	5.1-37.8	120
"	"	Hki	Passing	0.27	0.0013	0.0018	0.30	10-504	0-16.7	120
137	Häm.väylä	Häm	Basic	-0.22	0.0017	0.0020	0.91	232-1382	9.4-33.9	120
"	"	Häm	Passing	0.28	0.0014	0.0005	0.95	20-2117	0-6.4	120
137	Häm.väylä	Hki	Basic	-0.33	0.0019	0.0028	0.93	182-1339	6.1-30.9	120
"	"	Hki	Passing	0.24	0.0014	0.0019	0.92	99-1960	0-10	120
109	Lah.väylä	Hki	Basic	-0.46	0.0021	0.0047	0.97	540-1848	4.4-31.2	100
"	"	Hki	Passing	0.20	0.0014	0.0039	0.97	96-2247	0-9.8	100
109	Lah.väylä	Lahti	Basic	-0.32	0.0019	0.0005	0.96	239-1637	6.9-31.6	100
"	"	Lahti	Passing	0.31	0.0013	0.0024	0.85	16-1616	0-25	100

Table 40. Mean platoon length E(q) as a function of flow rate (q, veh/h) and heavy vehicles (HV%). ***Model: ln (E(q)) = a + b x q + c x HV%***

LAM sites	Locations	Dire-ction	Lane type	Inter-cept a	coeffic. b	coeffic. c	R^2	Flow range (veh/h)	Range of HV%	Speed limit (km/h)
112	Por.väylä	Hki	Basic	-0.30	0.0018	0.0076	0.78	239-864	4.7-30.6	120
"	"	Hki	Passing	0.34	0.0013	0.0352	0.44	154-670	0-7	120
131	Tuus.Väylä	Hki	Basic	-0.39	0.0020	0.0065	0.94	606-1634	4.8-21.1	100
"	"	Hki	Passing	0.29	0.0014	0.0120	0.94	206-2010	0-5.5	100
131	Tuus.Väylä	Tusla	Basic	-0.09	0.0019	0.0062	0.91	556-1415	0.4-23.6	100
"	"	Tusla	Passing	0.53	0.0013	0.0347	0.83	148-1392	0-5.5	100
128	Ring III	Vantaa	Basic	-0.29	0.0019	0.0004	0.68	132-1289	8-32	80
"	"	Vantaa	Passing	0.12	0.0019	0.0037	0.89	148-1529	0-18	80
128	Ring III	Knummi	Basic	0.24	0.0018	0.0057	0.80	416-1382	8-35	80
"	"	Knummi	Passing	0.69	0.0017	0.0019	0.90	116-1540	1-24	80

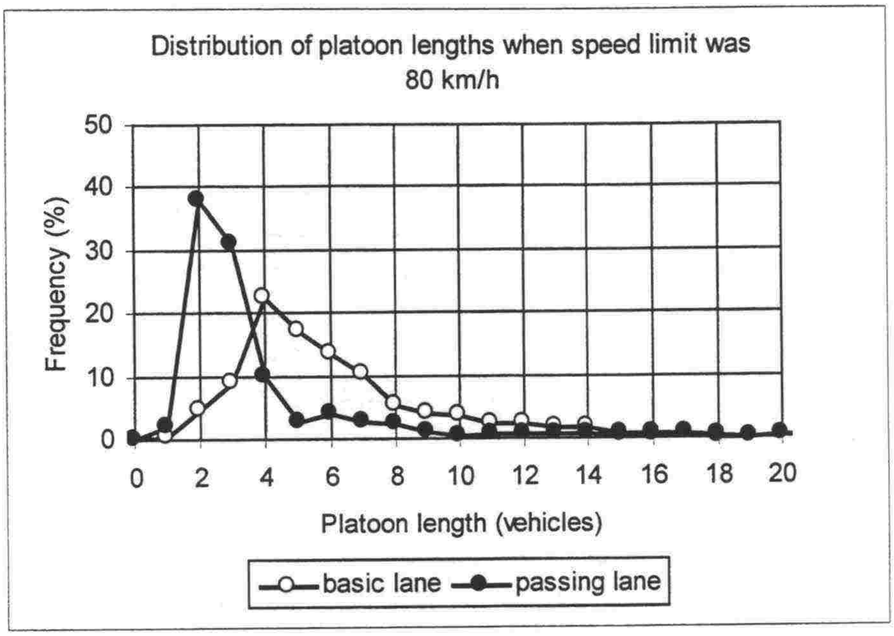

Figure 75. Distribution of platoon lengths (15-minute average) when speed limit was 80 km/h.

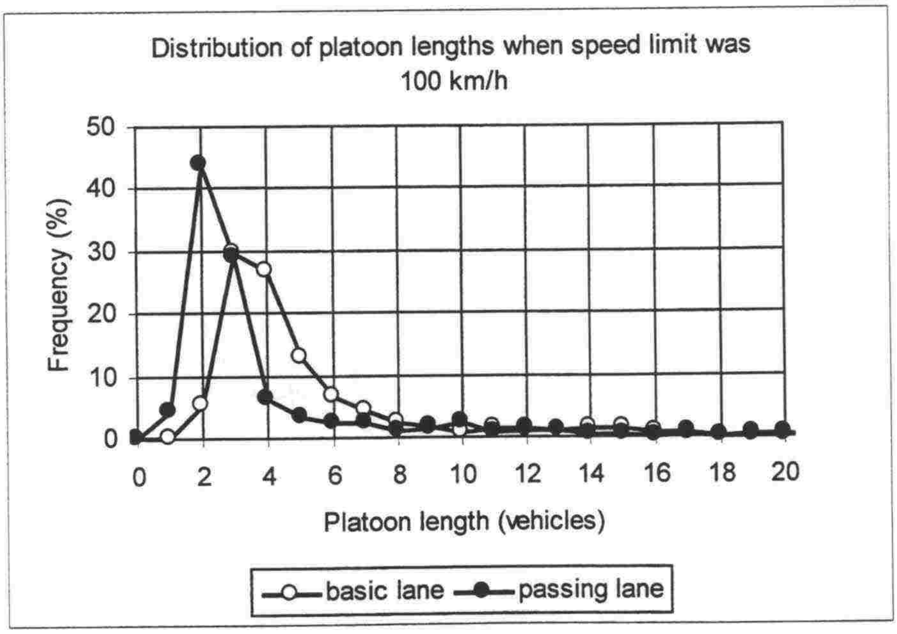

Figure 76. Distribution of platoon lengths (15-minute average) when speed limit was 100 km/h.

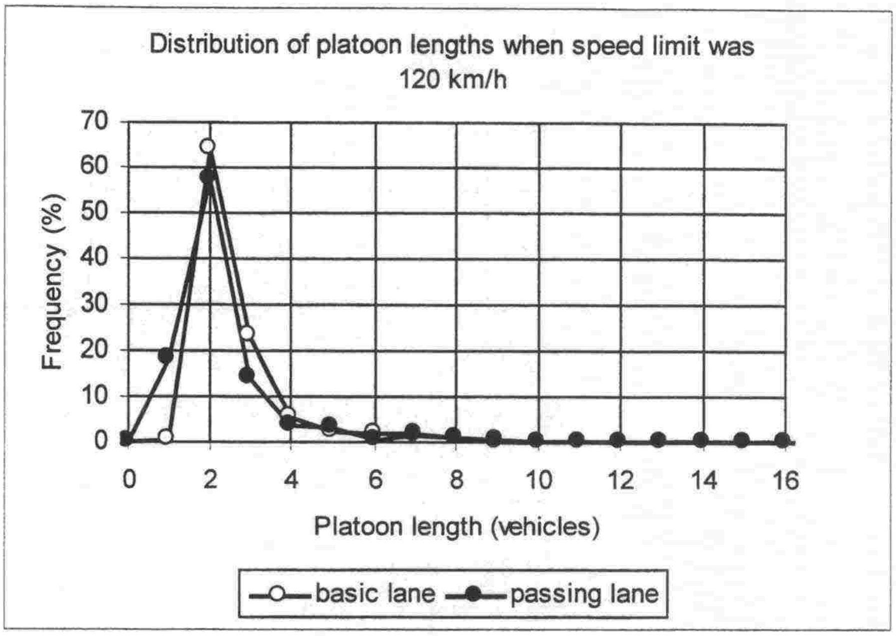

Figure 77. Distribution of platoon lengths (15-minute average) when speed limit was 120 km/h.

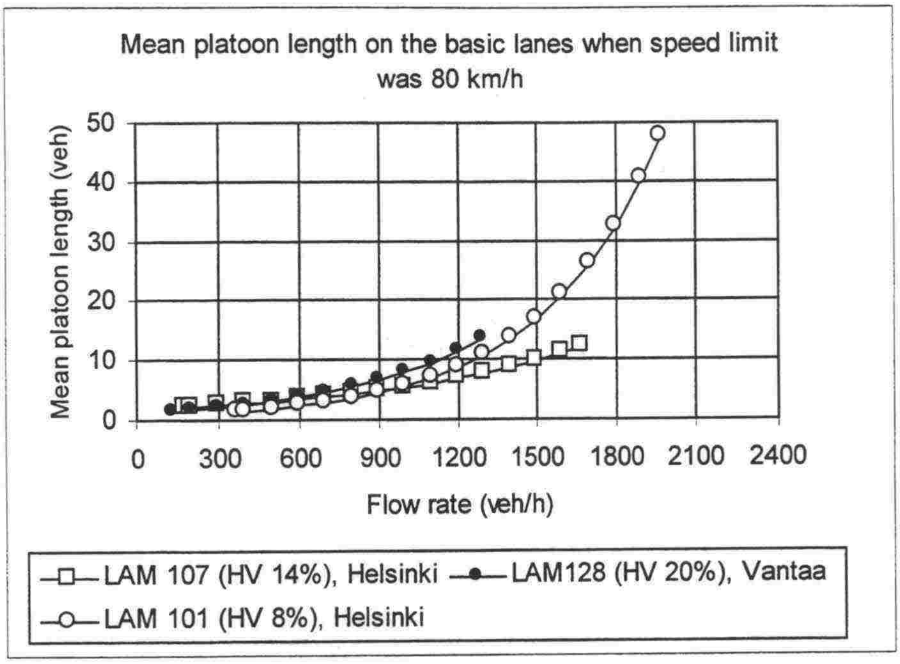

Figure 78. The relationships between mean platoon length and flow rate for average proportions of heavy vehicles on the basic lanes when speed limit was 80 km/h.

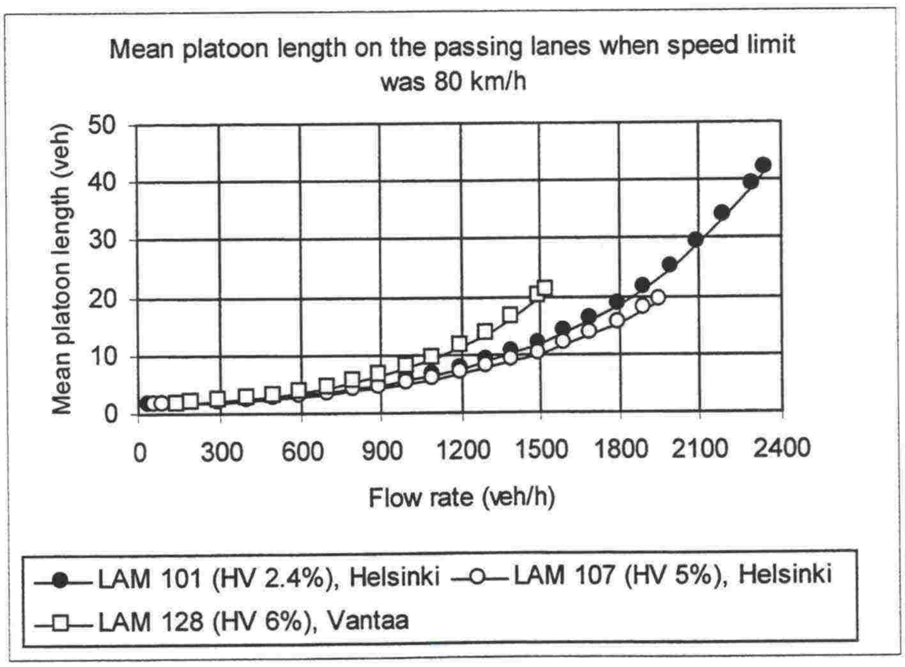

Figure 79. The relationships between mean platoon length and flow rate for average proportions of heavy vehicles on the passing lanes when speed limit was 80 km/h.

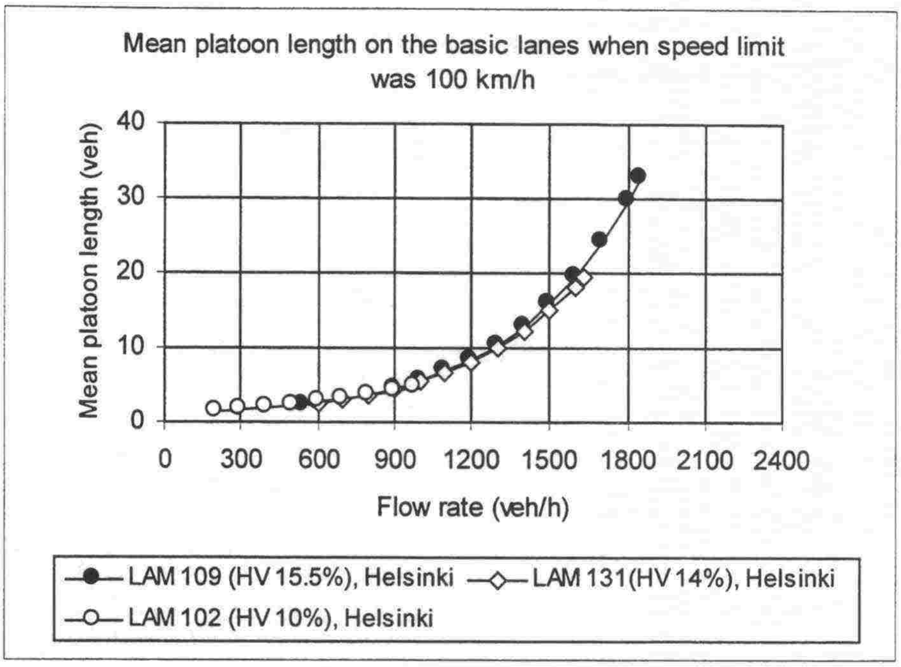

Figure 80. The relationships between mean platoon length and flow rate for average proportions of heavy vehicles on the basic lanes when speed limit was 100 km/h.

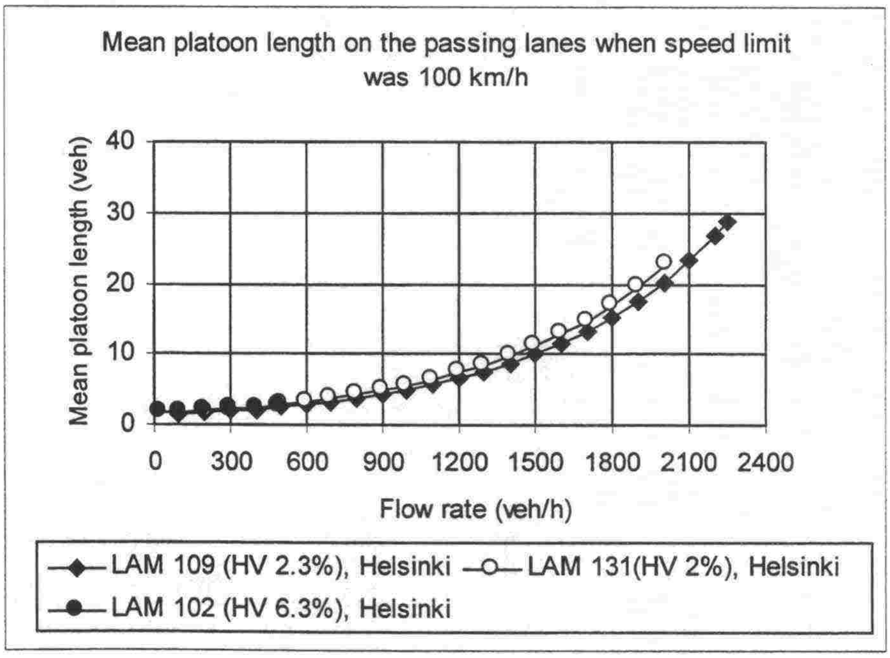

Figure 81. The relationships between mean platoon length and flow rate for average proportions of heavy vehicles on the passing lanes when speed limit was 100 km/h.

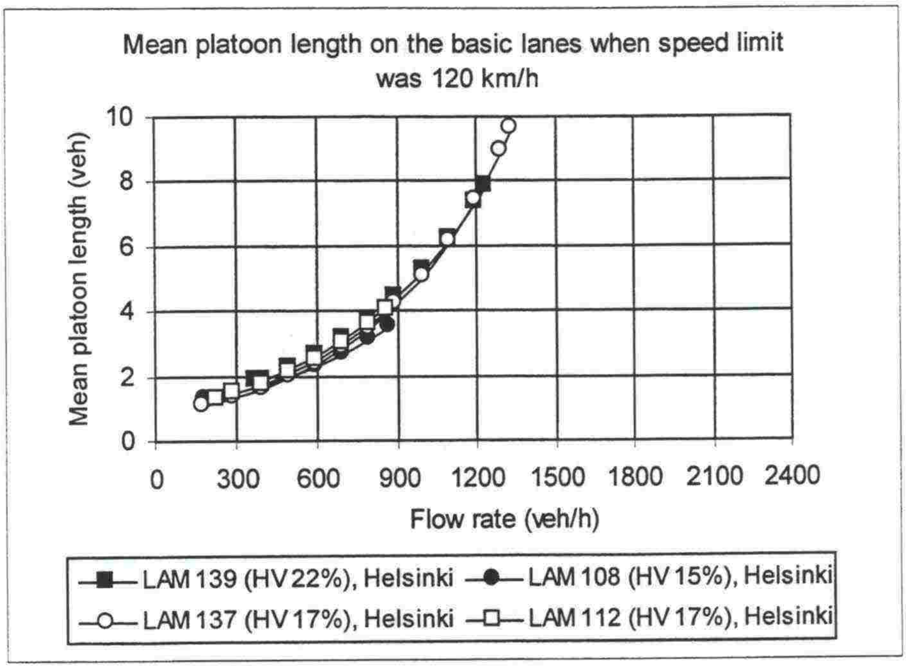

Figure 82. The relationships between mean platoon length and flow rate for average proportions of heavy vehicles on the basic lanes when speed limit was 120 km/h.

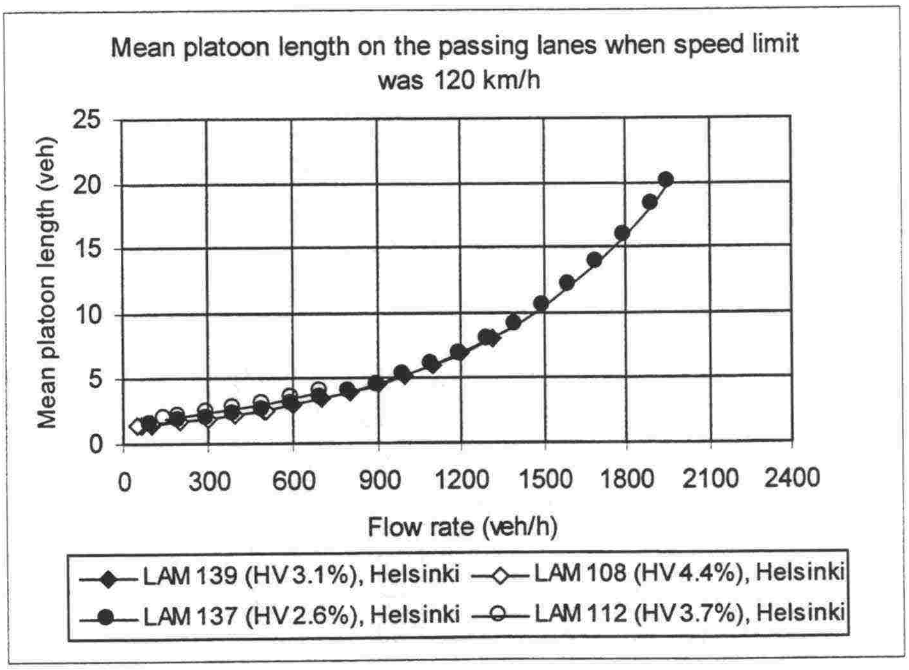

Figure 83. The relationships between mean platoon length and flow rate for average proportions of heavy vehicles on the passing lanes when speed limit was 120 km/h.

11 PASSENGER CAR EQUIVALENTS FOR HEAVY VEHICLES

11.1 General

To clarify the impact of heavy vehicles on traffic stream it is meaningful to estimate the passenger car equivalents (PCE) for heavy vehicles. There have been numbers of efforts to determine PCE values for various conditions, but most of these efforts have been focused on recalibrating or slightly modifying the methods outlined in HCM. In many earlier studies it was assumed that the car following behaviour in platoons is representative for capacity and consequently the PCE definition is based on a comparison of headways of trucks and cars in platoons (Botma 1994, Krammes & Crowley 1987). But in reality passenger car equivalents must be different for analyses of capacity, speed, platooning or other types of measures (van Aerde & Yagar 1988). Moreover, the PCE values are obviously different for different roads and lane types. This is because of geometric characteristics and speed limits.

Moreover, the performance of heavy vehicles on grades varies considerably depending on different categories of vehicles and individual differences between vehicles of a certain category. Heavy vehicles cover a wide cross-section of the road. They have physical and psychological impact on nearby vehicles (Krammes & Crowley 1987). According to HCM, any freeway grade of more than 0.8 km for grades less than 3 percent or 0.4 km for grades of 3 percent, or more, should be considered a separate segment. For such segments the analysis procedure of PCE values must include the upgrade and downgrade conditions (HCM 1994).

In this study the PCE values are estimated with regard to speed reduction, platoon leader, and follower in platoon. The 5-minute slices of travel speed data were used to estimate PCE values based on the speed reduction. The 15-minute slices of platooning data were used for the analyses of PCE values based on the vehicles in platoons.

11.2 PCE values based on speed reduction methods

PCE values were estimated for ramps, level sections, and for upgrades and downgrades of freeways. A multiple linear regression was structured to estimate the free speed and speed reduction coefficients as follows (see section 2.9):

$$V_{\text{tot or percentile}} = \text{Free speed} + (\alpha 1 \bullet \text{number of light vehicles}) + (\alpha 2 \bullet \text{number of heavy vehicles}) \tag{71}$$

In the above equation $\alpha 1$ and $\alpha 2$ are speed reduction coefficients and show the size of the speed reductions for each vehicle type. Therefore the PCE values can be estimated from the equation below (van Aerde & Yagar 1988):

$$PCE_{\text{for heavy vehicles based on speed reduction}} = \alpha_2/\alpha_1 \quad (72)$$

The 5-minute time slices of 15[th] percentile, average, and 85[th] percentile speeds were used to estimate speed reduction coefficients. The speed reduction coefficients were estimated for ramps, level sections, upgrades and downgrades separately. The obtained PCE values are given in *Tables 41-42* with a free speed intercept and set of speed reduction coefficients estimated for each type of speed.

Table 41. Speed reduction coefficients and PCE values for level sections and for ramps.

Description	**$V_{15\%}$ [level section]**	**$V_{average}$ [level section]**	**$V_{85\%}$ [level section]**	**$V_{15\%}$ [Ramp]**	**$V_{average}$ [Ramp]**	**$V_{85\%}$ [Ramp]**
Free speed	93.3	109.23	118.3	66.07	73.09	79.67
$\alpha1$	-0.0073	-0.0166	-0.0179	-0.0796	-0.0505	-0.0428
$\alpha2$	-0.0857	-0.1570	-0.1315	-0.5735	-0.1572	-0.0745
PCE values	**11.7**	**9.5**	**7.4**	**7.2**	**3.1**	**1.7**

Table 42. Speed reduction coefficients and PCE values for upgrades and downgrades.

Description grade 5%	**$V_{15\%}$ [upgrade]**	**$V_{average}$ [upgrade]**	**$V_{85\%}$ [upgrade]**	**$V_{15\%}$ [downgrade]**	**$V_{average}$ [downgrade]**	**$V_{85\%}$ [downgrade]**
Free speed	81.89	88.44	94.33	85.42	90.01	104.86
$\alpha1$	-0.0184	-0.0235	-0.0684	-0.0350	0.0278	-0.0861
$\alpha2$	-0.4074	-0.3020	-0.4739	-0.1638	0.0678	-0.2787
PCE values	**22.1**	**12.9**	**6.9**	**4.7**	**2.4**	**3.2**

11.3 PCE values based on platooning vehicles

Estimation of PCE values based on platooning assumptions is a useful method and used internationally for estimating level-of-service (Botma 1994). To quantify the quality of traffic operation it is necessary to estimate level-of-service of the lane type in question. The method used in this study has also been used elsewhere (van Aerde & Yagar 1988). Heavy vehicles often have lower desired speeds and poorer acceleration capabilities than passenger cars and are therefore more likely to be caught up by faster vehicles than passenger cars. It is obvious that the number of platooning vehicles or followers increases as the volume of traffic increases regardless lane type. For the estimation of PCE values based on platooning vehicles a number of multiple linear models were developed. The data from which the models were developed represent a range of flow rates from 20 to 1,597 vehicles per hour per lane. Therefore, to avoid extrapolating too far beyond the limits of the data, PCE values were estimated only for flow rates that approximate the upper limits of LOS A, B, and C. Separate multiple linear models for flow rates between 0 and 700 veh/h, 700 and 1,100 veh/h and 1,100 and 1,600 veh/h were developed for estimating PCE values. The PCE values were estimated separately for the road sections with speed limits 80 km/h, 100 km/h, and 120 km/h.

The multiple regression model for platooning vehicles as a function of light vehicles and heavy vehicles have the form (van Aerde & Yagar 1988)

$$N_{pl} = \alpha + \beta \bullet \text{light vehicles} + \gamma \bullet \text{heavy vehicles} \qquad (73)$$

where

N_{pl} = number of following vehicles with headway less than or equal to 5 seconds
α = intercept
β = coefficient of light vehicles
γ = coefficient of heavy vehicles.

$$PCE = \text{coefficient of heavy vehicles } \gamma \,/\, \text{coefficient of light vehicles } \beta \qquad (74)$$

The model parameters α, β, and γ are given in *Table 43*. The R^2 values and the PCE values are also given.

According to the analyses, at low flow rates, heavy vehicles produce about 1.1 followers compared to light vehicles, which produced only 0.82. Consequently, the PCE value is 1.34 (i.e. 1.1/0.82). This means that heavy vehicles produce, on the average, approximately 34% more followers than passenger cars do under the same traffic conditions and speed limits. On sections where the speed limit was 80 km/h, the PCE values were higher at low flow rates than at high flow rates on the basic lanes. On the passing lanes the estimated PCE values were higher at high flow rates than at low flow rate. On 100 km/h speed limit sections the PCE values were around 1.0 at all flow states. On the passing lane the estimated PCE value was higher when flow rate was within the range of 700-1,100 veh/h compared to other flow range. When speed limit was 120 km/h the estimated PCE values were similar at all flow rates on the basic lanes. On the passing lanes the estimated PCE values were higher at low than at high flow rates.

Despite that the platooning was higher at high flow rates, the estimated PCE values were sometimes lower at low flow rates and sometimes lower at high flow rates. Generally as the flow rate increased the average speed levels of the vehicles decreased and this decreasing trend is faster for light vehicles than for heavy vehicles. In this situation a platoon is able to catch another platoon and the proportion of heavy vehicles that are platoon leaders decreases. In this sense the PCE values used to be higher when flow rates were lower.

Table 43. PCE values based on number of platooning vehicles on the road sections where speed limit was 80 km/h, 100 km/h, and 120 km/h.

Speed limit 80 km/h	**LOS A Basic lane**	**LOS B Basic lane**	**LOS C Basic lane**	**LOS A Passing lane**	**LOS B Passing lane**	**LOS C Passing lane**
Intercept, α	-37.3	-83.6	-55.7	-20.2	-56.3	-93.9
coefficient for LV, β	0.82	1.07	1.07	0.75	1.01	1.14
coefficient for HV, γ	1.09	1.30	1.02	0.65	1.65	2.09
R^2 value	0.76	0.56	0.94	0.96	0.92	0.84
PCE values	**1.3**	**1.2**	**1.0**	**0.9**	**1.6**	**1.8**
Speed limit 100 km/h	**LOS A Basic lane**	**LOS B Basic lane**	**LOS C Basic lane**	**LOS A Passing lane**	**LOS B Passing lane**	**LOS C Passing lane**
Intercept, α	-65.5	-97.7	-45.3	-18.03	-81.0	-78.8
coefficient for LV, β	1.02	1.18	0.69	0.76	1.10	1.10
coefficient for HV, γ	0.91	1.14	0.69	0.77	2.35	1.51
R^2 value	0.95	0.98	0.73	0.89	0.97	0.92
PCE values	**0.9**	**1.0**	**1.0**	**1.0**	**2.1**	**1.4**
Speed limit 120 km/h	**LOS A Basic lane**	**LOS B Basic lane**	**LOS C Basic lane**	**LOS A Passing lane**	**LOS B Passing lane**	**LOS C Passing lane**
Intercept, α	-43.2	-99.9	-86.9	-13.36	-70.3	-86.71
coefficient for LV, β	0.84	1.18	1.13	0.66	1.07	1.13
coefficient for HV, γ	0.76	1.11	1.20	0.88	1.23	1.02
R^2 value	0.95	0.96	0.68	0.95	0.98	0.97
PCE values	**0.9**	**0.9**	**1.1**	**1.3**	**1.2**	**0.9**

11.4 PCE values based on leading vehicles

Generally large vehicles such as trucks, buses, and recreational vehicles, have a higher propensity to become platoon leaders than passenger cars. This hypothesis was analysed using the ratio of percentage of heavy vehicles leading to the percentage of heavy vehicles (HV%) in the traffic stream as PCE values (van Aerde & Yagar 1988). A simple linear regression for percentage of leading heavy vehicles as a function of percentage of total heavy vehicles in the traffic stream was established and given in the following manner:

$$PL_{HV,\ 80\ km/h,\ basic\ lane} = 0.85 + 1.53 \times HV\% \qquad R^2 = 0.60 \quad (75)$$

$$PL_{HV,\ 80\ km/h,\ passing\ lane} = 2.42 + 0.88 \times HV\% \qquad R^2 = 0.41 \quad (76)$$

$$PL_{HV,\ 100\ km/h,\ basic\ lane} = 3.36 + 1.20 \times HV\% \qquad R^2 = 0.54 \quad (77)$$
$$PL_{HV,\ 100\ km/h,\ passing\ lane} = 1.17 + 0.87 \times HV\% \qquad R^2 = 0.42 \quad (78)$$

$$PL_{HV,\ 120\ km/h,\ basic\ lane} = 1.51 + 1.01 \times HV\% \qquad R^2 = 0.74 \quad (79)$$
$$PL_{HV,\ 120\ km/h,\ passing\ lane} = 1.40 + 0.70 \times HV\% \qquad R^2 = 0.61 \quad (80)$$

where :

PL_{HV} = percentage of heavy vehicles leading platoon
HV% = percentage of heavy vehicles in traffic stream

$$PCE_{based\ on\ platoon\ leader} = PL_{HV}/HV\% \qquad (81)$$

By substituting the average proportions of heavy vehicles in the above models and by calculating the ratio of the PL_{HV}-% to the HV% the PCE values for different speed limits and lanes were obtained. The results are summarized in *Table 44.*

Table 44. PCE values based on platoon leaders.

Descriptions	Basic lane PCE	Passing lane PCE	Basic lane (Average HV%)	Passing lane (Average HV%)
Speed limit 80 km/h	1.6	1.4	14	5
Speed limit 100 km/h	1.4	1.3	15	2.5
Speed limit 120 km/h	1.1	1.1	18	3.4

12 DISCUSSION AND CONCLUSIONS

The results of an empirical analysis of the impact of heavy vehicles on freeway traffic flow have been presented in this study. The studied characteristics were speed, flow, gap, platooning, geometry of the road and ramps, and vehicle composition. The impact of heavy vehicles on platooning and on speeds has been quantified using multivariate regression analyses. Separate relationships were developed for ramps and freeway sections with different geometric characteristics. Acceleration and deceleration rates when following a heavy vehicle at a constant distance were calculated. Passenger car equivalents were estimated using three different factors, namely speed reduction, platooning vehicles, and platoon leaders.

Heavy vehicles' deceleration and acceleration rates varied between –1.1 and 1.1 m/s^2. Average acceleration was a little higher than average deceleration. In Kosonen (1996) the average acceleration rate was a little higher than the average deceleration rate. The acceleration and deceleration rates presented in this report are not directly comparable with previous findings (Kosonen 1996) because the values were calculated from speeds of heavy vehicles, which were driven on a freeway with high speeds. According to the results from a heavy vehicle simulator the acceleration rate of a heavy vehicle varied between 0.5 and 0.3 m/s^2 when the speed of the vehicle varied between 70 and 83 km/h (Lehmuskoski 1998). Compared to Lehmuskoski (1998) it was found that the momentary acceleration rates in this study varied between 0 and 1.1 m/s^2 and the average rates between 0.29 and 0.32 m/s^2 when the speed of the vehicles varied between 70 and 82 km/h. In general, the deceleration rate is higher than the acceleration rate when a vehicle is compelled to reduce its speed in an inconvenient situation. If there is no impeding vehicle then the driver of a vehicle continues to accelerate unless he/she has reached the speed that he/she desires. The fluctuation of the acceleration and deceleration rates is high in an unstable traffic situation. This fluctuation diminishes as soon as drivers reach their desired speed. In this study it was found that the standard deviation of acceleration (acceleration noise) varied between 0.08 and 0.7 m/s^2 and the average standard deviation was 0.17 m/s^2. According to heavy vehicle simulator the standard deviation of acceleration varied between 0.07 and 0.21 m/s^2 (Lehmuskoski 1998). The acceleration noises were at a minimum when the speed was between 85 and 95 km/h. This might be the reason of uniform gaps with preceding vehicle and uniform speed of the heavy vehicle itself (Drew 1968).

The mean gap when a heavy vehicle followed a heavy vehicle was larger than when a heavy vehicle followed a light vehicle. A light vehicle followed a light vehicle at a larger gap than a light vehicle followed a heavy vehicle. The peak was around 3 sec when a heavy vehicle followed a heavy vehicle and around 2 seconds for other vehicle combinations (light-heavy, heavy-light, light-light). According to Parker (1996) heavy vehicles followed heavy vehicles with a larger gap than heavy vehicles followed light vehicles. The gaps that drivers usually accept depend on drivers' behaviours. Aggressive drivers accept smaller following gaps than cautious drivers (Parker 1996).

According to this study the gaps that a test vehicle maintain to the vehicle in front just before overtaking are a little larger than the gaps to the vehicle behind just after overtaking. In general, the following gap distribution gets narrower as the speed of the leading vehicles get smaller (Lloyd & Gerlough 1976). The gap that a driver accepts just before overtaking obviously depends on available passing sight distance, drivers' behaviour, sex and his/her trip purposes. On the other hand the gap just after overtaking depends on the speed level of overtaking and overtaken vehicles.

The mode of the gaps on the basic lanes was between 1 and 2 seconds and on passing lanes varied between 1 and 2 seconds. The value of mode was higher on low speed limit areas than on high speed limit areas as well on passing as on basic lanes. About 33% of the vehicles on basic lane and about 28% on passing lane maintained gaps around 2 seconds when speed limit was 80 km/h. On the other hand, on sections where speed limits were 100 or 120 km/h the percentage of short gaps increased on the passing lane and decreased on the basic lane. The standard deviation of gaps was about 2-3 folds higher on passing lanes than on basic lanes on sites where speed limit was 80 km/h. This differences were even 4-5 folds on sites where speed limit was 100 or 120 km/h. According to Sirkiä (1987) drivers usually maintain shorter headways on passing lanes than on basic lanes. The peak of shorter headways was higher at low speed limit areas than at high speed limit areas. The standard deviation of headways was higher on passing lanes than on basic lanes. There is no big difference between gaps at low and high speed limit areas for high flow rates (Pursula 1988).

The running speed of the heavy vehicles varied between 76 and 98 km/h and the average running speed varied between 84 and 91 km/h on road sections where speed limit was 120 km/h (Hämeenlinnanväylä). On the other hand, the point speed on this road section fluctuated between 60 and 110 km/h and the 15-minute space mean speed varied between 80 and 95 km/h (LAM 137). The standard deviation of the point speed was much higher than the standard deviation of running speed. The differences between space mean speed and average running speed are not very a lot. This is because the running speeds are the speeds of a few drivers, whereas the spot speeds are the speed of a large number of drivers. On the other hand the running speed was collected during off peak hours, whereas the spot speeds were gathered for whole days.

The travel speeds of light and heavy vehicles on level terrain, upgrades and downgrades varied a lot. The average travel speed of heavy vehicles was about 9 km/h lower than the speed of light vehicles on a level terrain. According to a Canadian study the speed of heavy vehicles on level terrain is about 2.5 to 5 km/h smaller than that of light vehicles (Archilla & Morrall 1994). Heavy vehicles were affected more on upgrades than on downgrades. On road sections where the grades were quite gentle (1.2-1.6%) heavy vehicles were only slightly affected both on upgrades and downgrades. In this study it was found that about

90% of trucks with trailer were driven with speed below 90 km/h when speed limit was 120 km/h and grades were 1.2-1.6%. The average speed of heavy vehicles on upgrades was about 15 to 26 km/h slower than that of light vehicles when speed limit 120 km/h and grades were 1.2-1.6%. The corresponding values on downgrades were about 13 to 29 km/h.

According to HCM (1994) road sections with downgrades less than 3% are usually comparable with level terrain. The speeds of the heavy vehicles are only slightly affected on road sections with grade less than 3%. In this study it was found that travel speeds of 80% of the drivers who drive trucks with trailer varied between 55 and 80 km/h and of 20% of the drivers between 80-85 km/h on a 'steep' upgrade (5%). On the downgrade (5%) in the opposite direction about 60% of the drivers of trucks with trailer drove their vehicles with speeds between 55-80 km/h and the rest of the drivers drove with speeds between 80-90 km/h. The average speed of heavy vehicles on upgrades (5%) is about 8 km/h and on downgrades (5%) about 5 km/h smaller than that of light vehicles. However, according to Archilla & Morrall (1994), speeds are quite different on steep downgrades. Heavy vehicle speeds are severely affected by steep downgrades (4.5-6.5%). The average speed of heavy vehicles was about 8 to 36 km/h smaller than that of light vehicles on a steep downgrade. According to Hall et al. (1994) speeds of light vehicles increased by hilliness falls and decreased by hilliness rises greater than 4%. The speeds of the heavy vehicles were also affected by hilliness rises (Hall et. al. 1994). According to a Finnish study the speed of heavy vehicles is about 8 km/h smaller on a road section with 4% grade than on a level terrain (Roine 1973).

The travel speeds were quite different on different ramps and varied a lot with the geometry of the ramps. In this study it was found that the speeds of heavy vehicles on loop ramps varied between15 and 45 km/h and these speeds of light vehicles between 25 and 60 km/h. The speeds of heavy vehicles on jug-handle ramps varied between 35 and 80 km/h and the speeds of light vehicles between 40 and 90 km/h. The speeds of heavy vehicles on loop ramps were affected more than the speeds of light vehicles. On loop ramps the speed of light vehicles was about 9 km/h bigger than that of heavy vehicles. On jug-handle ramps the speed of light vehicles was about 4 to 13 km/h bigger than that of heavy vehicles. The share of heavy vehicles on the ramp also has a considerable influence on average speed. In addition the radius of the curves has impact on travel speeds. Light vehicles are also slightly affected, although the effects are more severe for the heavy vehicles. Ramps with large radii seem to have little effect on speed. These are the reasons why the speeds on loop ramps are much lower than the speeds on jug-handle ramps.

The traffic flows were stable during the measurements on all highways except on Ring Road III. The speeds between peak hours and off peak hours varied a lot on Ring Road III, especially towards Vantaa. The speed differences between peak hours and off peak hours were slightly higher on sections with the speed limit 80 km/h than on sections with the speed limits 100 km/h or 120 km/h. The variations of speed of the heavy vehicles between peak hours and off peak hours were hardly noticeable.

The speed differences between light and heavy vehicles also varied because of different speed limits. The speed differences between light and heavy vehicles at 120 km/h areas were about 3 to 4 times higher than at speed limits 80 & 100 km/h. The speed differences between light and heavy vehicles were higher on the basic lanes than on the passing lanes. The mean speed differences between light and heavy vehicles were about 3 times higher at 100 km/h speed limit sites and 5-6 times higher at 120 km/h speed limit sections than the speed differences at 80 km/h speed limit sites.

The speed decrease because of increasing flow rate varied remarkably at different LAM sites. The speed drops 2.4 km/h – 16.1 km/h per 1,000 veh/h on different speed limit areas. The speed decrease was a little faster on low speed limit areas than on high speed limit areas. According to a previous study, the speed decrease was a little faster on high speed (100 km/h) limit areas than on low speed limit (80 km/h) areas (Sirkiä 1987) .On sections where the speed limit was 80 km/h, the speed decrease because of flow rate varied between 2.9 and 16.1 km/h per 1,000 veh/h. The corresponding values in Sirkiä (1987) varied between 3.3 and 6.5 km/h per 1,000 vehicles. On sections where speed limit was 100 km/h, the speed decreased between 2.8 – 7.9 km/h per 1,000 veh/h. The corresponding values in Sirkiä (1987) were between 6.0 – 10.3 km/h. The reasons of opposite results might be the influence of vehicle composition and local geometry. On 80 km/h speed limit areas the average free speed (desired) of light vehicles was about 6 to11 km/h higher than the speed limit. The corresponding values were 3-9 km/h for heavy vehicles. The average free speed for all vehicles was about 5 to 10 km/h higher than speed limit. On sections where speed limit was 100 km/h, the average free speed of light vehicles was about 3 km/h lower to 6 km/h higher than speed limit. The average free speed of heavy vehicles was about 10 to 17 km/h lower than speed limit. Average free speed (light and heavy) was about 5 km/h lower to 3 km/h higher than speed limit. This is in accordance with previous findings (Sirkiä 1987, Pursula 1988). On sections where speed limit was 120 km/h, the average free speed of light vehicles was about 1 to 12 km/h lower and of heavy vehicles was about 25 to 37 km/h lower than speed limit. The overall speed decreased as flow rate, proportion of heavy vehicles, and hilliness of the road sections increased.

In general, drivers experience high speed when traffic circumstances are convenient for them. On passing lanes the overall speeds are higher than on the basic lanes. This is in accordance with previous findings (Pursula 1988). In this study it was found that about 50% of the drivers on upgrade and 62% of the drivers on downgrade violated the speed limit when speed limit was 80 km/h. On level terrain about 20-60% of drivers of heavy vehicles and 57-61% of drivers of light vehicles violated the speed limit. About 54% of drivers on basic lane and about 74% of drivers on passing lane violated speed limit. On sections where speed limit was 100 km/h, about 2% of drivers of heavy vehicles and 37% of drivers of light vehicles violated the speed limit on basic lane. On the passing lanes, about 3% of drivers of heavy vehicles and about 67% of drivers of light vehicles violated speed limit. About 38% of drivers on basic lane and about 80% of drivers on passing lane were violated speed limit. According to a previous study, about 20-50% of drivers on basic lane and 20-95% of drivers on passing lane violated speed limit on 80 km/h speed limit areas. About 5-15% of drivers on basic lane and 10-85% on passing lane violated the speed limit when speed limit was 100 km/h (Pursula 1988). On sections where speed limit was 120 km/h, about 20-40% drivers of light vehicles on basic lane and 38-51% on passing lane violated speed limit. On upgrades about 20% and on downgrades about 30% of the drivers violated the speed limit.

The reduction of speeds because of the proportion of heavy vehicles varied remarkably on different lanes. The speed reduction coefficient was sometimes higher on the basic lane and sometimes higher on the passing lane. The overall speed decreased as proportion of heavy vehicle increased and a little faster at high speed limit areas (100 and 120 km/h) than at low speed limit areas (80 km/h). Normally at high speed limit areas the speed differences between light and heavy vehicles are much higher compared to low speed limit areas. However, as the flow rate and proportion of heavy vehicle increased, overtaking facility decreased, therefore in this circumstance the drivers of high speed vehicles (light vehicles) are compelled to slow down their vehicle instantaneously. This might be one reason why the speed decrease was a little faster at high speed limit areas than at low speed limit areas.

In this study it was found that the number of platooning vehicles increased as flow rate increased. This is in accordance with previous findings (Pursula & Enberg 1991, Enberg & Pursula 1997). The impact of heavy vehicles on platooning was also different on different lanes. In some cases the impact of heavy vehicles on platooning was found to be negligible. This means that the proportion of heavy vehicles had no systematic influence on platooning. This is in accordance with previous findings (Botma 1994). The mean lengths of the platoons were a little shorter at high speed limit areas than at low speed limit areas. At low speed limit areas average platooning speeds were a little higher than the speed limit, whereas the average platooning speeds at high speed limit areas were much lower than the speed limit. The reason of that is that most of drivers in low speed areas are able to maintain their desired speed even they drive in platoon ($h \leq 5$ sec). On the other hand at high speed limit areas, it is impossible to maintain desired speed when driving in platoon, which lead to overtaking. These might be the reasons why the lengths of platoons are a little shorter at high speed limit areas than at low speed limit areas. In this study it was found that the percentages of heavy vehicles that are platoon leaders were much higher than the percentages on heavy vehicles in traffic stream. This is in accordance with previous findings (Archilla & Morrall 1994, van Aerde & Yagar 1988, Botma 1994). The differences between the percentage of heavy vehicles that are platoon leaders and the percentage of heavy vehicle in traffic stream were much higher at low speed limit areas than at high speed limit areas.

The PCE (Passenger Car Equivalents) values were sometimes higher on the basic lane and sometimes higher on the passing lane. The estimated PCE values also varied between different speed limits. The PCE values estimated based on the speed reduction method were much higher than those estimated based on platooning vehicles and platoon leaders. This is in accordance with previous findings (van Aerde & Yagar 1988). The PCE values estimated for low speed limit areas, in terms of platooning vehicles, were quite similar to those suggested by van Aerde & Yagar (1988). The PCE values estimated for LOS A-C were a little smaller compared to the PCE values found in an American study (Mahmassani & Young 1987). The PCE values estimated in terms of platoon leader were more appropriate, and reliable compared to other estimation procedures (HCM 1994, Botma 1994).

This study gives information about the basic traffic flow characteristics and especially about heavy vehicles on Finnish freeways and other divided multilane highways. The data analyses were performed from both a microscopic and a macroscopic point of view. The results can be used for calibrating and validating a freeway micro simulation program as well as for extending the knowledge of Finnish freeway traffic flow. The gaps for four vehicle following combinations and gaps to the heavy vehicle in front just before overtaking and to the heavy vehicle behind after overtaking can be used for calibration purposes. The acceleration and deceleration rates when the test vehicle followed a heavy vehicle at a constant distance are also useful parameters for calibrating a simulation program. The results of speed distributions on different ramps, upgrades, downgrades, basic lanes, passing lanes, and on different speed limit sections can also be used as calibration parameters. Passenger car equivalents, speed-flow relationships and platooning on different speed limit sections can also be used for validating a freeway simulation program.

13 SUMMARY

General

The impact of heavy vehicles on the traffic stream is different of that of light vehicles. This is because they are larger than passenger cars and their operating capabilities are inferior to those of light vehicles. Heavy vehicles often have lower desired speeds and poorer acceleration capabilities than passenger cars and therefore they are more likely to be caught by fast moving vehicles, which leads to higher platooning and overtakings. Heavy vehicles also have lower speed limit (80 km/h) than passenger cars. However, on four-lane freeways the impact of heavy vehicles is not as severe as on two-lane two-way highways.

In this study the impact of heavy vehicles on Finnish freeway traffic flow has been analysed. The study is based on field measurements and literature review. The idea was to clarify the impact of heavy vehicles on freeway traffic flow and at the same time to procure parameters to extend the use of the microsimulation program HUTSIM from traffic signal simulation to freeway simulation.

Data collection and methods

Information on travel speeds was collected using the license plate method on three highways (Turunväylä, Hämeenlinnanväylä, and Ring Road III). Information about travel speeds on different ramps was also gathered with the same method. The basic properties of the traffic flow such as the 85th percentile, 15th percentile, and average travel speeds were studied from the data.

To observe the variations in behaviour between drivers and differences in the accelerations and decelerations of heavy vehicles an instrumented vehicle was driven in the traffic stream on Hämeenlinnanväylä between Keimola and Hyvinkää. Information about travel time, travel distance, speed and overtaking maneuvers of the test vehicle, as well as the distance between the test vehicle and the vehicle in front were stored in the computer memory. The data were gathered using test drivers and by observing the behaviour of other drivers. The data analyses were concentrated on the behaviour and impact of heavy vehicles. Some measurements were also done on Ring Road III between Isontammentie and Vanha Porvoontie to get some information about the speed level on a partly signal controlled section on a dual carriageway road.

The space mean speeds of each vehicle type were studied from the point measurement data gathered from different LAM sites. In addition platooning, gaps, and passenger car equivalents were analysed. Multivariate regression techniques were used to explain the relationship between the speed of the light and heavy vehicles, flow rate, and proportion of heavy vehicles. An artificial dummy variable was used to distinguish between heavy and light vehicles.

Speed level, acceleration rate, and gap

The speed level of the heavy vehicles on Hämeenlinnanväylä, measured by following a heavy vehicle with an instrumented vehicle at a constant distance of about 40 m, fluctuated between 75 and 96 km/h towards Hyvinkää and between 78 and 96 km/h towards Keimola. The average running speed on the whole section varied between 84 and 91 km/h towards Hyvinkää and between 87 and 88 km/h towards Keimola depending on measurement period. The standard deviation of speed was very small, it varied between 1.6 and 3.1 km/h towards Hyvinkää and between 2.1 and 2.4 km/h towards Keimola.

The route of the measurements on Ring III was sliced into seven sections and the average travel speeds, 85th percentile speeds, and 15th percentile speeds for each section were calculated. The main idea was to show the real speed level throughout the road sections as well as the running speeds on the road sections with free flow between the intersections. The average running speed varied from one measurement period to another and from section to section, too. Very high speeds compared to other sections were found on the road section between Tikkuritie and Vanha Porvoontie. The average running speed on this section varied between 82 and 83 km/h and the standard deviation of speed between 5.8 and 7.5 km/h. The speed limit was 80 km/h. The average speed on the whole road section varied between 63 and 83 km/h. Especially low speeds were found on the road section between Isontammentie and Hämenlinnanväylä.

When following a heavy vehicle at a constant distance the deceleration and acceleration rate of the test vehicle varied between –1.1 and 1.1 m/s^2. The average acceleration rate was 0.33 m/s^2 and the average deceleration rate was –0.31 m/s^2. The acceleration noise is the standard deviation of the accelerations. The acceleration noise of the test vehicle varied between 0.1 and 0.7 m/s^2 when following a heavy vehicle.

The gap to the vehicle in front just before overtaking and the gap to the vehicle behind just after overtaking a heavy vehicle were calculated from the data gathered by the instrumented vehicle using test drivers. The average gap before overtaking was 1.9 seconds and it fluctuated between 0.8 and 3.6 seconds. The corresponding value after the overtaking was 1.4 seconds and varied between 0.3 and 4.8 seconds. About 58% of the gap data were around 2 seconds just before overtaking and about 50% were close to 2 seconds just after overtaking. Based on data gathered from the LAM 128 on Ring Road III, the mode of the gap was around 2 seconds when a light vehicle was following a heavy vehicle for a flow rate of 1,228 veh/h/lane. At the same flow rate the mean gap was 2.2 seconds when a light vehicle was following a heavy vehicle and 3.2 seconds when a heavy vehicle was following a light vehicle. On sections where speed limit was 80 km/h the mode of gap was around 2 seconds on both lanes. At high speed limit areas the percentages of short gaps were much higher on the passing lane than on the basic lane. At 100 km/h speed limit areas about 47% of the gaps were between 0.38 and 2 seconds on the passing lane, whereas only 36% of the gaps were between 0.41 and 2 seconds. Similarly, where the speed limit was 120 km/h, about 42% of the gaps were between 0.25 and 2 sec on passing lane and only 20% of the gaps were between 0.32 and 2 seconds.

Travel speeds and effects of road geometry

Travel speeds on entrance ramps, level sections, upgrades, and downgrades were measured with the license plate method using video cameras. The speed distributions for each individual vehicle type were analysed. In addition, average travel speeds, 85^{th} percentile speeds, 15^{th} percentile speeds, and speeds of the heavy and light vehicles were studied.

On the level section before Tuomarila downgrade on Turunväylä towards Turku the travel speeds of the light vehicles varied between 75 and 120 km/h and of the heavy vehicles between 60 and 110 km/h. The overall speed differences between light and heavy vehicles varied between 0 and 16 km/h (average speed difference 10 km/h). The maximum 5-minutes flow rate was 1,924 veh/h for both lanes together. The speed for light vehicles decreased by 4.3 km/h and the speed for heavy vehicles by 4.2 km/h when the flow increased by 1,000 veh/h.

The speeds on grades depend on the hilliness. On a freeway (Hämeenlinnanväylä, hilliness 12 m/km) upgrade the speed differences between light and heavy vehicles varied between 0 and 35 km/h (average speed difference 26 km/h) and on the downgrade in the opposite direction between 0 and 37 km/h (average 29 km/h). On Ring III (Kalkkikallio upgrade and downgrade, hilliness 50 m/km) the corresponding speed difference varied between 0 and 8 km/h (average 5 km/h) on the upgrade and between 0 and 11 km/h (average 6 km/h) on the downgrade. On Turunväylä (Tuomarila upgrade and downgrade, hilliness 16 m/km), the speed differences varied between 0 and 15 km/h (average 15 km/h) on the upgrade and between 0 and 16 km/h (average 13 km/h) on the downgrade. The speed differences between light and heavy vehicles varied a lot at different speed limit areas. The speed differences between light vehicles and heavy vehicles were higher on the basic lane than on the passing lane.

The speed decrease was faster with increasing proportion of heavy vehicles on upgrades than on downgrades. For example, at Kalkkikallio upgrade on Ring III the average speed decrease was 4 km/h per 10% heavy vehicles on the upgrade and only 1 km/h per 10% heavy vehicles on the downgrade. On level sections the average travel speed decreased about 6 km/h per 10% of heavy vehicle increase.

The travel speeds on loop ramps varied between 15 and 60 km/h, whereas this speed varied between 35 and 90 km/h on jug-handle ramps. The shape and geometry of the ramps had, of course, an impact on the travel speeds. For example on the jug-handle ramp from Ring I to Länsiväylä, the speed differences between light and heavy vehicles varied between 0 and 5 km/h (average 4 km/h) and on the loop ramp from Ring I to Turunväylä between 0 and 12 km/h (average 9 km/h). The average travel speeds increase when the radii of the ramps increase. Similarly, average travel speeds decrease when the hilliness of the ramps increases.

Space mean speed and flow rate

The speed-flow relationships were studied on Ring Road III and on six freeways with different speed limits. The space mean speed decreased with flow rate a little faster on Ring Road III than on freeways. The speed decrease was also a little faster at LAM sites where speed limit was 80 km/h than at sites with speed limits 100 km/h or 120 km/h. Generally high speed decreases faster with flow rate that low speed. In this study the flow rate at high speed limit areas was lower compared to low speed limit areas. This might be one reason why the speed decrease with flow rate was a little faster at low speed limit areas than at high speed limit areas. The effects of flow rate on space mean speed were of the same order on both lanes. However, the speed decrease seemed to be a little faster on the basic lane than on the passing lane. At some sites it was noticed that the speed increased as the flow rate increased. The reasons behind that were low flow rates and small percentages of heavy vehicles and the fact that there was little relationship between speed and flow on freeway sections with high speed level.

The overall speed-flow relationships were noticeably affected by the percentages of heavy vehicles. The effect was different on basic lanes and passing lanes and also different on freeways with different speed limits. The share of heavy vehicles on the passing lane was only 2-7%. On the basic lane the share of heavy vehicles was 10-20%. The effect of the heavy vehicles on space mean speed was sometimes higher on the basic lane and sometimes higher on the passing lane, though the proportion of heavy vehicles always was higher on the basic lane. The effect of heavy vehicles on speed was usually higher as the proportion of heavy vehicles was higher and varied slightly between different sites with the same speed limit.

The differences between space mean speed of the light and heavy vehicles were higher on the basic lanes than on the passing lanes. When speed limit was 80 km/h space mean speeds of the heavy vehicles were about 3-6 km/h lower on the basic lanes and 3-5 km/h lower on the passing lanes compared to the space mean speed of the light vehicles. The corresponding values were 8-14 km/h on the basic lanes and 6-14 km/h on the passing lanes when speed limit was 100 km/h. At sites where the speed limit was 120 km/h the space mean speeds of the heavy vehicles were 18-24 lower on the basic lanes and 15-26 km/h lower on the passing lanes.

Cumulative speed distributions curves were drawn for the basic lanes and passing lanes using data from different LAM sites. When speed limit was 80 km/h the speed differences varied a lot depending on measurement site, lane type and speed limit. The speed differences between light and heavy vehicles varied between 0 and 10 km/h on the basic lanes and between 0 and 20 km/h on the passing lanes. At LAM sites where speed limit was 100 km/h the speed differences varied between 0 and 15 km/h on the basic lane and between 0 and 8 km/h on the passing lane. The corresponding values varied between 0 and 27 km/h on the basic lane and between 0 and 25 km/h on the passing lanes, when speed limit was 120 km/h.

The speeds at peak hours were 0 and 40 km/h lower than at off peak hours for both light and heavy vehicles towards Vantaa at Ring Road III. Towards Kirkkonummi the corresponding values varied between 0 and 5 km/h. On the freeways the speed difference between peak hours and off peak hours varied between 0 and 8 km/h for light vehicles, but for heavy vehicles the speed difference could barely be seen.

Platooning

The effect of heavy vehicles on platooning (5 seconds platoon criterion) was higher on the basic lane than on passing lane. The effect of heavy vehicles varied with road, speed limit and lane type. For example, at sites with speed limit 80 km/h the platoon percentages were higher than at sites with speed limit 120 km/h. The mean lengths of the platoons were longer at sites with 80 km/h speed limit than at sites with speed limit 120 km/h. Especially at low flow rates the effect of heavy vehicles on platooning was negligible (but always increasingly affecting) on four-lane freeways. This is because the faster vehicles are able to overtake the slower vehicles.

The percentages of heavy vehicles leading platoons were greater than the percentages of these vehicles in the traffic stream. Heavy vehicles had higher propensity to become a platoon leader at sites where speed limit was 80 km/h than at sites where speed limit was 120 km/h. At sites where speed limit was 80 km/h about 31% of the heavy vehicles were leaders, even if they were only 20% of the traffic stream on the basic lane. On the passing lane about 8% of the heavy vehicles were leaders even if they were only 6% of the traffic stream. At sites where the speed limit was 100 km/h about 21% of the heavy vehicles were leaders though they were only 16% of the traffic stream on the basic lanes. On the passing lanes the corresponding values were 4 and 2%. At sites where the speed limit was 120 km/h about 19% of the heavy vehicles were leaders although they were only 17% of the traffic stream on the basic lanes. On the passing lanes the corresponding values were 4 and 3%.

Passenger car equivalent

The PCE values were calculated with regard to speed reduction, followers in platoon and platoon leaders. The speed reduction coefficients were estimated using multiple linear regression for 15th percentile speed, average speed, and 85th percentile speed for light vehicles and heavy vehicles. Those speed reduction coefficients indicate the relative size of speed reductions for each vehicle type and on behalf of those coefficients the PCE values for heavy vehicles were calculated. The average PCE value for heavy vehicles was 9.5 on the level sections, 12.9 on the upgrades, 2.4 on the downgrades, and 3.1 on the ramps.

The PCE values based on platooning vehicles (following vehicles) were estimated only for flow rates that approximate the upper limits of LOS A, B, and C. The flow rates 700, 1,100, and 1,600 veh/h/lane define the upper boundaries for LOS A, B, and C for basic freeway segments. Multiple regression analyses were used to estimate the coefficients of the independent variables. Those coefficients indicated the influence of each vehicle type on platooning and using those coefficients the PCE values for following vehicles were calculated. The PCE values based on platooning vehicles were much lower than the corresponding values for speed reduction. The PCE value based on platooning vehicles for heavy vehicles on the basic lane was 1.2 when the speed limit was 80 km/h and 1.0 when the speed limit was 100 km/h or 120 km/h. On the passing lane the PCE value was 1.4 when the speed limit was 80 km/h, 1.5 when the speed limit was 100 km/h, and 1.1 when speed limit was 120 km/h.

The PCE values based platoon leaders were estimated using linear regression analyses. The proportion of heavy vehicles leading of the total leading vehicles was considered dependent variable and the proportion of heavy vehicles of the whole traffic stream was considered independent variable in the regression model. The PCE values were calculated as the ratio of the percentage of heavy vehicles leading to the percentage of heavy vehicles in the traffic stream. Based on this method the PCE value for heavy vehicles on the basic lane was 1.6 when the speed limit was 80 km/h, 1.4 when the speed limit was 100 km/h, and 1.1 when the speed limit was 120 km/h. On the passing lane the corresponding values were 1.4, 1.3, and 1.1.

Conclusions

On the freeways the traffic flows were stable during the field measurements. On Ring Road III, a number of unstable 15-minutes flows with speeds below 60 km/h were observed. The speed differences between peak hours and off peak hours were noticeably higher on Ring Road III compared to freeways.

The overall speed differences between light and heavy vehicles increased with increasing speed limit. The speed differences were higher on the basic lane than on the passing lane. The speeds of the heavy vehicles on upgrades were lower than their speeds on level sections and downgrades. The average travel speed was about 11 km/h lower on loop ramps than other ramp types.

The overall speed decreased as flow rate and proportion of heavy vehicle increased. On Ring III the space mean speed decrease with flow rate was much faster than on the freeways for both light and heavy vehicles. At sites where speed limit was 80 km/h the space mean speed decrease with flow rate and proportion of heavy vehicles was also faster than at sites with speed limit 100 km/h or 120 km/h.

The space mean speeds of light vehicles were different for different roads but the speeds of heavy vehicles were on the same level for all roads. The platoon percentages were higher at sites with speed limit 80 km/h than with speed limit 120 km/h. The mean length of the platoons was shorter at sites with 120 km/h speed limit than at sites with 80 km/h speed limit. The PCE values varied based on estimation procedures. The PCE value was found to be much higher when estimated based on speed reduction than when estimated based on platooning

vehicles and platoon leaders. The PCE values estimated in terms of platoon leaders were more appropriate compared to other estimation procedures.

This study gives information about the basic traffic flow characteristics and especially about heavy vehicles on Finnish freeways and other divided multilane highways. The data analyses were performed from both a microscopic and a macroscopic point of view. The results can be used for calibrating and validating a freeway micro simulation program as well as for extending the knowledge of Finnish freeway traffic flow. The gaps for four (heavy-light, light-heavy, heavy-heavy, light-light) vehicle following combinations and gaps to the heavy vehicle in front just before overtaking and to the heavy vehicle behind after overtaking can be used for calibration purposes. Gap distributions on different speed limit (80, 100, and 120 km/h) areas can be used for calibrating the freeway simulation program. The acceleration and deceleration rates when the test vehicle followed a heavy vehicle at a constant distance are also useful parameters for calibrating a simulation program. The results of speed distributions on ramps, upgrades, downgrades, basic lanes, passing lanes and on different speed limit sections can also be used as calibration parameters. Passenger car equivalents, speed-flow relationships and platooning on different speed limit sections can be used for validating a freeway simulation program.

14 YHTEENVETO

Yleistä

Raskaiden ajoneuvojen vaikutus moottoriteiden liikennevirtaan poikkeaa kevyiden ajoneuvojen vaikutuksesta. Raskaat ajoneuvot ovat kooltaan isoja ja niiden ohjattavuus on huonompi kuin kevyiden ajoneuvojen. Moottoriteillä raskaiden ajoneuvojen vaikutus on kuitenkin pienempi kuin kaksikaistaisilla maanteillä. Raskaiden ajoneuvojen tavoitenopeus on usein pienempi ja niiden kiihtyvyysominaisuudet ovat heikompia kuin kevyiden ajoneuvojen. Raskaiden ajoneuvojen nopeusrajoitus (80 km/h) vaikuttaa myös nopeuteen. Näistä syistä nopeammat ajoneuvot saavuttavat raskaat ajoneuvot, mikä johtaa jononmuodostukseen ja ohituksiin.

Tutkimus perustuu kenttämittauksiin ja kirjallisuustutkimukseen. Tarkoituksena oli selvittää raskaiden ajoneuvojen vaikutusta korkealuokkaisten väylien liikennevirtaan ja samalla hankkia parametreja HUTSIM-nimisen mikroskooppisen liikenteensimulointiohjelman käyttöalueen laajentamista varten liikennevalojen toiminnan simuloinnista moottoritiesimulointiin.

Menetelmät

Rekisteritunnusmenetelmällä kerättiin matkanopeustietoja Turunväylällä, Hämeenlinnanväylällä ja Kehä III:lla sekä erilaisilta rampeilta. Liikennevirran perusominaisuuksia, kuten 15 ja 85 %:n nopeudet sekä keskimääräiset matkanopeudet, selvitettiin aineistoista.

Eri kuljettajien käyttäytymiserot ja raskaiden ajoneuvojen kiihtyvyys- ja hidastuvuuserot tutkittiin ajamalla instrumentoidulla ajoneuvolla Hämeenlinnanväylällä Keimolan ja Hyvinkään välillä. Tietoja matka-ajasta, kuljetusta matkasta, nopeudesta ja ohitustapahtumista sekä etäisyys edellä ajavaan ajoneuvoon tallennettiin tietokoneeseen instrumentoidussa autossa. Tutkimuksessa käytettiin koekuljettajia sekä tarkkailtiin muiden ajoneuvojen käyttäytymistä. Aineistojen käsittelyssä keskityttiin raskaiden ajoneuvojen vaikutuksiin ja käyttäytymiseen. Kehä III:lla, Isontammentien ja Vanhan Porvoontien välillä, tehtiin myös muutamia mittauksia, joiden tarkoituksena oli selvittää matkanopeustaso osittain valo-ohjauksisella kaksiajorataisella tiellä.

Eri ajoneuvotyyppien keskinopeudet tutkittiin liikenteen automaattisen mittausjärjestelmän (LAM) avulla kerätyistä pistenopeusaineistoista. Lisäksi tutkittiin jononmuodostusta, aikavälejä ja henkilöautoekvivalentteja. Raskaiden ja kevyiden ajoneuvojen keskinopeuksien, liikennemäärän ja raskaiden ajoneuvojen osuuden väliset riippuvaisuudet tutkittiin regressioanalyysillä. Raskaiden ja kevyiden ajoneuvojen nopeudet eroteltiin dummy-muuttujalla.

Nopeustaso, kiihtyvyys ja aikaväli

Instrumentoidun auton nopeustaso Hämeenlinnanväylällä, kun se ajoi raskaan ajoneuvon takana noin 40 m vakioetäisyydellä, vaihteli välillä 75-96 km/h Hyvinkään suuntaan ja välillä 78-96 km/h Keimolan suuntaan. Mittauksesta riippuen keskimääräinen matkanopeus koko matkalla (30 km) vaihteli välillä 84-91 km/h Hyvinkään suuntaan ja välillä 87-88 km/h Keimolan suuntaan. Matkanopeuden keskihajonta oli pieni, se vaihteli välillä 1,6-3,1 km/h Hyvinkään suuntaan ja välillä 2,1-2,4 km/h Keimolan suuntaan.

Kehä III:lla mittausreitti jaettiin seitsemään jaksoon ja jokaiselle jaksolle laskettiin keskimääräiset matkanopeudet sekä 85 ja 15 %:n nopeudet. Tarkoituksena oli selvittää nopeustaso sekä koko tiejaksolla että liittymien välisillä vapaan liikenteen tiejaksoilla. Keskimääräinen matkanopeus vaihteli mittauksesta toiseen ja myös eri tiejaksoilla. Muihin tiejaksoihin verrattuna nopeudet välillä Tikkuritie-Vanha Porvoontie olivat selvästi korkeampia. Tällä välillä keskimääräinen matkanopeus vaihteli välillä 82-83 km/h ja keskihajonta välillä 5,8-7,5 km/h. Nopeusrajoitus oli 80 km/h. Koko tiejaksolla keskimääräinen matkanopeus vaihteli välillä 63-83 km/h. Erityisen alhaisia nopeudet olivat välillä Isontammentie-Hämeenlinnanväylä.

Kiihtyvyys ja hidastuvuus vaihtelivat välillä -1,1 - 1,1 m/s^2, kun instrumentoitu auto seurasi raskasta ajoneuvoa 40 m vakioetäisyydellä. Keskimääräinen kiihtyvyys oli 0,33 m/s^2 ja keskimääräinen hidastuvuus -0,31 m/s^2. Raskaan ajoneuvon seurannassa kiihtyvyyshajonta (kiihtyvyyksien keskihajonta tietyllä tiejaksolla) vaihteli välillä 0,1-0,7 m/s^2.

Koekuljettaja-aineistoista laskettu instrumentoidun auton keskimääräinen nettoaikaväli edellä ajavaan raskaaseen ajoneuvoon juuri ennen ohitukseen lähtöä oli 1,9 s ja se vaihteli välillä 0,8-3,6 s. Ohituksen jälkeen, kun instrumentoitu auto palasi omalle kaistalleen, takana olevaan raskaaseen ajoneuvoon jätettiin keskimäärin 1,4 s väli, joka vaihteli välillä 0,3-4,8 s. Noin 58 % nettoaikaväleistä edellä ajavaan oli suunnilleen 2 s juuri ennen ohitukseen lähtöä ja noin 50 % väleistä taakse jäävään oli suunnilleen 2 s. LAM-pisteessä 128 Kehä III:lla yleisin nettoaikaväli oli noin 2 s kevyen ajoneuvon seuratessa raskasta ajoneuvoa liikennemäärällä 1228 ajon/h. Samalla liikennemäärällä keskimääräinen nettoaikaväli oli 2,2 s, kun kevyt ajoneuvo seurasi raskasta ajoneuvoa, ja 3,2 s raskaan ajoneuvon seuratessa kevyttä ajoneuvoa.

Matkanopeudet ja geometrian vaikutukset

Matkanopeudet liittymisrampeilla, tasaisilla tiejaksoilla sekä ala- ja ylämäissä tutkittiin rekisteritunnusmenetelmällä videokameroita käyttäen. Rekisteritunnusaineistoista laskettiin eri ajoneuvotyyppien matkanopeusjakaumat sekä keskimääräiset matkanopeudet ja 15 ja 85 %:n nopeudet kevyille ja raskaille ajoneuvoille erikseen.

Tasaisella tiejaksolla, Turunväylällä, kevyiden ajoneuvojen matkanopeus vaihteli välillä 75-120 km/h ja raskaiden ajoneuvojen välillä 60-110 km/h. Kevyiden ja raskaiden ajoneuvojen nopeusero vaihteli välillä 0-16 km/h (keskiarvo 10 km/h). Suurin havaittu 5 min liikennemäärä yhteen suuntaan oli 1924 ajon/h. Kevyiden ajoneuvojen keskimatkanopeus laski 4,3 km/h ja raskaiden ajoneuvojen 4,2 km/h liikennemäärän kasvaessa 1000 ajon/h.

Ylä- ja alamäissä nopeudet ovat riippuvaisia mäkisyydestä. Hämeenlinnanväylällä kevyiden ja raskaiden ajoneuvojen nopeusero ylämäessä (mäkisyys 12 m/km, nop.raj. 120 km/h) vaihteli välillä 0-35 km/h (keskiarvo 26 km/h) ja toiseen suuntaan alamäkeen välillä 0-37 km/h (keskiarvo 29 km/h). Kalkkikallion ylämäessä Kehä III:lla (mäkisyys 50 m/km, nop.raj. 80 km/h) vastaava nopeusero vaihteli välillä 0-8 km/h (keskiarvo 5 km/h) ja alamäessä välillä 0-11 km/h (keskiarvo 6 km/h). Tuomarilan ylämäessä Turunväylällä (mäkisyys 16 m/km, nop.raj. 120 km/h) nopeusero vaihteli välillä 0-15 km/h (keskiarvo 12 km/h) ja alamäessä välillä 0-16 km/h (keskiarvo 13 km/h). Kevyiden ja raskaiden ajoneuvojen nopeusero vaihteli nopeusrajoituksen mukaan. Peruskaistalla nopeusero oli suurempi kuin ohituskaistalla.

Matkanopeuden aleneminen raskaiden ajoneuvojen osuuden kasvaessa oli suurempi ylämäessä kuin alamäessä. Esimerkiksi Kalkkikallion ylämäessä Kehä III:lla matkanopeus laski keskimäärin 4 km/h ja alamäessä vain 1 km/h raskaiden ajoneuvojen osuuden kasvaessa 10 %. Tasaisella tiejaksolla matkanopeus aleni 6 km/h raskaiden ajoneuvojen osuuden kasvaessa 10 %.

Liittymisramppien muoto ja geometria vaikuttivat luonnollisesti matkanopeuksiin. Silmukkarampeilla keskimääräiset matkanopeudet vaihtelivat välillä 25-75 km/h ja puolisuorilla rampeilla välillä 40-90 km/h. Esimerkiksi Kehä I:n ja Länsiväylän välisellä puolisuoralla rampilla Helsingin suuntaan raskaiden ja kevyiden ajoneuvojen nopeusero oli 0-5 km/h (keskiarvo 4 km/h) ja Kehä I:n ja Turunväylän välisellä silmukkarampilla Turun suuntaan 0-12 km/h (keskiarvo 9 km/h).

Keskinopeus ja liikennemäärä

Keskinopeuden ja liikennemäärän väliset riippuvaisuudet tutkittiin Kehä III:lla ja kuudella moottoritiellä eri nopeusrajoitusalueilla. Kehä III:lla keskinopeus laski hieman nopeammin liikennemäärän kasvaessa kuin moottoriteillä. Nopeuden lasku oli hieman nopeampaa nopeusrajoituksella 80 km/h kuin nopeusrajoituksilla 100 ja 120 km/h. Liikennemäärän kasvun vaikutus oli samaa suuruusluokkaa molemmilla kaistoilla. Joissakin LAM-pisteissä keskinopeus kasvoi liikennemäärän kasvaessa. Syinä saattavat olla pienet liikennemäärät ja raskaiden ajoneuvojen vähyys tai se tosiasia että korkeatasoisilla väylillä suurilla nopeusrajoituksilla liikennemäärän kasvu ei vaikuta keskinopeuteen.

Raskaiden ajoneuvojen osuus vaikutti huomattavasti nopeus-liikennemäärä riippuvaisuuteen. Vaikutus oli erilainen peruskaistalla kuin ohituskaistalla ja se vaihteli eri moottoriteiden ja nopeusrajoitusten mukaan. Raskaiden ajoneuvojen osuus ohituskaistalla oli 2-7 % ja peruskaistalla 10-20 %. Raskaiden ajoneuvojen vaikutus keskinopeuteen oli joskus suurempi peruskaistalla ja joskus ohituskaistalla, vaikka raskaiden ajoneuvojen osuus aina oli suurempi peruskaistalla. Vaikutus oli yleensä sitä suurempi mitä suurempi oli raskaiden ajoneuvojen osuus, ja se vaihteli myös hieman eri pisteiden välillä, vaikka nopeusrajoitus oli sama.

Erot kevyiden ja raskaiden ajoneuvojen keskinopeudessa olivat joskus suurempia peruskaistoilla ja joskus ohituskaistoilla. Raskaiden ajoneuvojen keskinopeus verrattuna kevyiden ajoneuvojen keskinopeuteen oli noin 3-6 km/h alhaisempi peruskaistalla ja noin 3-5 km/h alhaisempi ohituskaistoilla nopeusrajoituksella 80 km/h. Vastaavat arvot nopeusrajoituksen ollessa 100 km/h olivat 8-14 km/h peruskaistalla ja 6-14 km/h ohituskaistalla. Nopeusrajoituksen ollessa 120 km/h nopeuserot olivat 18-24 km/h ja 15-26 km/h.

Eri LAM-pisteiden kumulatiiviset nopeusjakaumakäyrät piirrettiin kevyille ja raskaille ajoneuvoille sekä perus- että ohituskaistoille. Nopeuserot raskaiden ja kevyiden ajoneuvojen välillä vaihtelivat suuresti mittauspisteen, kaistatyypin ja nopeusrajoituksen mukaan. Nopeusrajoituksen ollessa 80 km/h nopeusero oli 0-10 km/h peruskaistalla ja 0-20 km/h ohituskaistalla. Nopeusrajoituksen ollessa 100 km/h nopeusero oli 0-15 km/h peruskaistalla ja 0-8 km/h ohituskaistalla. Vastaavat nopeuserot nopeusrajoituksen ollessa 120 km/h olivat 0-27 km/h ja 0-25 km/h.

Kehä III:lla Vantaan suuntaan nopeusero ruuhkaliikenteen ja ruuhka-ajan ulkopuolisen liikenteen välillä oli 0-40 km/h sekä kevyille että raskaille ajoneuvoille. Kirkkonummen suuntaan vastaava ero oli 0-5 km/h. Moottoriteillä kevyiden ajoneuvojen nopeus oli 0-8 km/h alhaisempi ruuhkaliikenteessä kuin ruuhka-ajan ulkopuolisessa liikenteessä, mutta raskaiden ajoneuvojen osalta nopeusero oli tuskin havaittavissa.

Jononmuodostus

Raskaiden ajoneuvojen vaikutus jononmuodostukseen (jonokriteeri 5 s) oli suurempi peruskaistalla kuin ohituskaistalla. Vaikutus vaihteli tien, nopeusrajoituksen ja kaistatyypin mukaan. Esimerkiksi nopeusrajoituksen ollessa 80 km/h jonoprosentti oli suurempi kuin rajoituksen ollessa 120 km/h. Jonojen keskipituus oli suurempi nopeusrajoituksella 80 km/h kuin nopeusrajoituksella 120 km/h. Erityisesti pienillä liikennemäärillä raskaiden ajoneuvojen vaikutus jononmuodostukseen on erittäin pieni mutta kuitenkin lisäävästi vaikuttava nelikaistaisella kaksiajorataisella moottoritiellä. Syynä on luonnollisesti moottoritien nopeille ajoneuvoille antamat ohitusmahdollisuudet.

Raskaiden ajoneuvojen osuus jonon johtajista oli suurempi kuin niiden osuus kaikista ajoneuvoista. Raskailla ajoneuvoilla oli suurempi taipumus tulla jonon johtajaksi nopeusrajoituksen ollessa 80 km/h kuin sen ollessa 120 km/h. Nopeusrajoituksella 80 km/h noin 31 % raskaista ajoneuvoista oli jonon johtajia, vaikka niiden osuus peruskaistan liikenteestä oli vain 20 %. Ohituskaistalla noin 8 % raskaista ajoneuvoista oli jonon johtajia vaikka niiden osuus liikenteestä oli vain 6 %. Nopeusrajoituksella 100 km/h 21 % raskaista ajoneuvoista oli jonon johtajia kun niiden osuus koko peruskaistan liikenteestä oli 16 %. Ohituskaistalla vastaavat arvot olivat 4 % ja 2 %. Nopeusrajoituksen ollessa 120 km/h 19 %

raskaista ajoneuvoista oli jonon johtajia kun niiden osuus koko peruskaistan liikenteestä oli 17 %. Ohituskaistalla prosenttiosuudet olivat 4 % ja 3 %.

Henkilöautoekvivalentti

Henkilöautoekvivalentit (Passenger Car Equivalents, PCE) laskettiin nopeuden alenemisen, jonossa olevien ja jonon johtajien perusteella. Nopeuden alenemiseen liittyvät kertoimet laskettiin regressioanalyysillä raskaiden ja kevyiden ajoneuvojen keskinopeuksille sekä 15 ja 85 %:n nopeuksille. Nopeuskertoimet ilmaisevat ajoneuvotyyppien nopeuden alenemista ja kertoimien avulla raskaille ajoneuvoille laskettiin henkilöautoekvivalentit. Keskimääräinen PCE-arvo raskaille ajoneuvoille oli 9,5 tasaisilla jaksoilla, 12,9 ylämäissä, 2,4 alamäissä ja 3,1 rampeilla.

Jonossa olevien ajoneuvojen perusteella laskettavat PCE-arvot laskettiin ainoastaan palvelutasojen A, B ja C ylärajojen liikennemäärille. Moottoriteiden linjaosuuksilla nämä liikennemäärät ovat 700, 1100 ja 1600 ajon/h/kaista. Kertoimet laskettiin regressioanalyysillä ja ne ilmaisevat ajoneuvotyypin vaikutusta jononmuodostukseen. Niiden avulla lasketut PCE-arvot olivat pienempiä kuin nopeuden alenemiseen perustuvat arvot. Peruskaistalla keskimääräinen PCE-arvo raskaille ajoneuvoille jonossa oli 1,2 nopeusrajoituksen ollessa 80 km/h peruskaistalla ja 1,0 nopeusrajoituksen ollessa 100 tai 120 km/h. Ohituskaistalla vastaavat PCE-arvot olivat 1,4 (80 km/h), 1,5 (100 km/h) ja 1,1 (120 km/h).

Jonon johtajien perusteella laskettavat PCE-arvot laskettiin myös regressioanalyysin avulla. Raskaiden ajoneuvojen osuutta kaikista jonon johtajista käytettiin selitettävänä muuttujana ja niiden osuutta kaikista ajoneuvoista käytettiin selittäjänä. PCE-arvot laskettiin raskaiden jonon johtajien osuuden suhteena raskaiden ajoneuvojen osuuteen kaikista ajoneuvoista. Tällä menetelmällä laskettu PCE-arvo peruskaistalle oli 1,6 nopeusrajoituksen ollessa 80 km/h, 1,4 nopeusrajoituksen ollessa 100 km/h ja 1,1 nopeusrajoituksen ollessa 120 km/h. Vastaavat PCE-arvot ohituskaistalle olivat 1,4, 1,3 ja 1,1.

Johtopäätöksiä

Liikennevirrassa ei esiintynyt huomattavia häiriöitä kenttämittausten aikana. Ainoastaan Kehä III:lla mitattiin muutama epävakaa havainto, jolloin keskinopeudet putosivat alle 60 km/h. Moottoriteihin verrattuna nopeusero ruuhkaliikenteen ja ruuhka-ajan ulkopuolisen liikenteen välillä oli selvästi suurempi Kehä III:lla.

Raskaiden ja kevyiden ajoneuvojen nopeusero kasvoi nopeusrajoituksen mukana. Nopeuserot olivat suurempia perus- kuin ohituskaistalla. Raskaiden ajoneuvojen nopeus ylämäissä oli alhaisempi kuin alamäissä ja tasaisilla tiejaksoilla. Silmukkarampilla keskimatkanopeus oli noin 11 km/h alhaisempi kuin muilla ramppityypeillä.

Nopeus laski liikennemäärän ja raskaiden ajoneuvojen osuuden kasvaessa. Kehä III:lla nopeuden lasku oli nopeampaa kuin moottoriteillä sekä kevyille että raskaille ajoneuvoille. Nopeusrajoitusalueella 80 km/h keskinopeus laski nopeammin liikennemäärän ja raskaiden ajoneuvojen osuuden kasvaessa kuin nopeusrajoitusalueilla 100 ja 120 km/h.

Tutkimus antaa tietoja liikennevirran perusominaisuuksista ja erityisesti raskaiden ajoneuvojen vaikutuksista moottoriteillä ja muilla korkealuokkaisilla kaksiajorataisilla väylillä. Aineistojen käsittely ja analyysi tehtiin sekä mikroskooppisella että makroskooppisella tasolla. Tuloksia voidaan käyttää moottoritieliikenteen mikrosimulointiohjelman kalibrointia ja validointia varten sekä suomalaisen liikennevirtaosaamisen laajentamista varten.

Nettoaikavälit edellä ajavaan raskaaseen ajoneuvoon juuri ennen ohitukseen lähtöä ja takana olevaan raskaaseen ajoneuvoon palattaessa omalle kaistalle ovat hyödyllisiä parametreja simulointiohjelman kalibroimisessa, kuten myös nettoaikavälit neljälle eri ajoneuvoseurantayhdistelmälle. Kiihtyvyys- ja hidastuvuusarvot instrumentoidun auton seuratessa raskasta ajoneuvoa vakioetäisyydellä ovat myös käyttökelpoisia kalibrointiparametreja.

Matkanopeusjakaumat rampeilla, ylä- ja alamäissä, peruskaistalla, ohituskaistalla ja eri nopeusrajoitusalueilla ovat myös tärkeitä. Tietoja henkilöautoekvivalenteista, keskinopeus-liikennemäärä riippuvaisuudesta ja jononmuodostuksesta eri nopeusrajoitusalueilla voidaan käyttää simulointiohjelman validointia varten.

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16 APPENDICES

Appendix A – Map of the measurement locations.

Appendix B – Acceleration rate of the following vehicle on Ring III.

Appendix C – Travel speed distributions on ramps, grades, and level sections.

Appendix D – Configuration of ramps, which were included in this study.

Appendix E – Speed-flow relationships on upgrades and downgrades.

Appendix F – The LAM sites used in this study and the data collection dates and times.

Appendix G – Space mean speed as a function of flow rate on freeways, regression coefficients.

Appendix H – Space mean speed as a function of flow rate on freeways, regression lines.

Appendix I – Space mean speed and average flow rate at different LAM sites.

Appendix J – Cumulative speed distributions based on data from different LAM sites.

Appendix K – Space mean speed and flow rate at different LAM sites, both lanes together.

Appendix L—Space mean speed and flow rate on basic lane and passing lane at different speed limit areas.

Appendix A – Map of the measurement locations

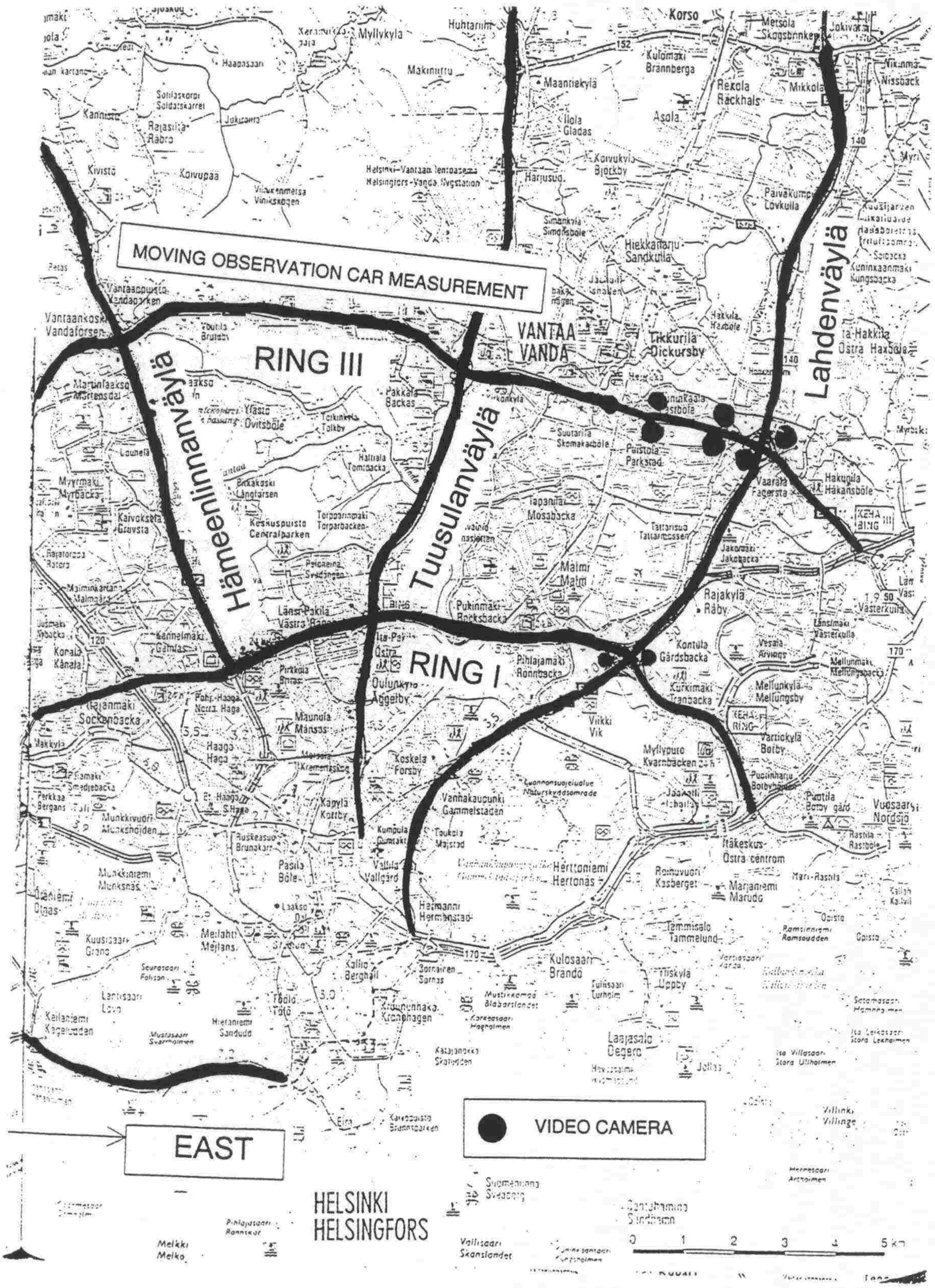

Figure A –1. Map of the measurement locations.

Appendix A – Map of the measurement locations

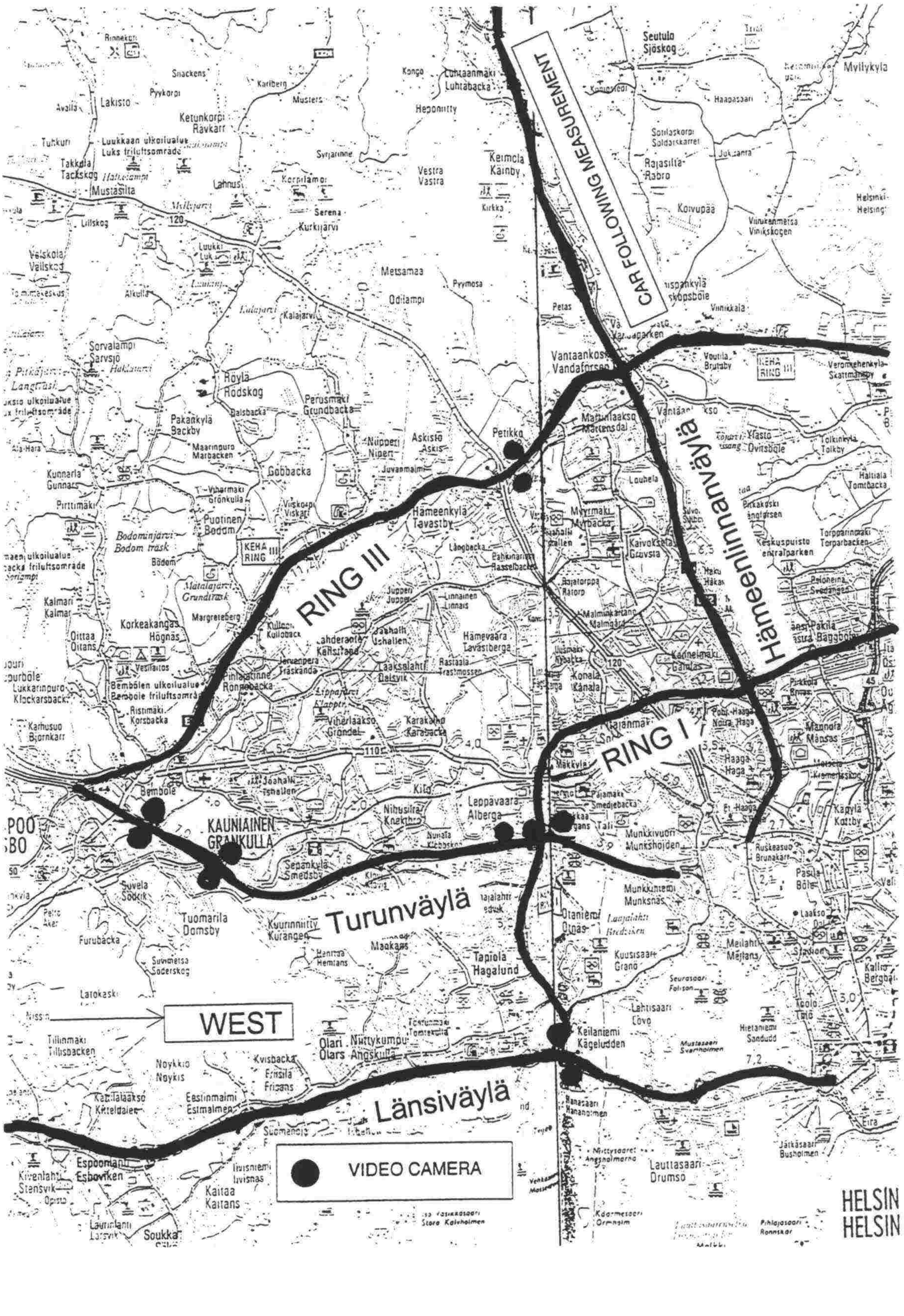

Figure A-2. Map of the measurement locations.

Appendix A – Map of the measurement locations

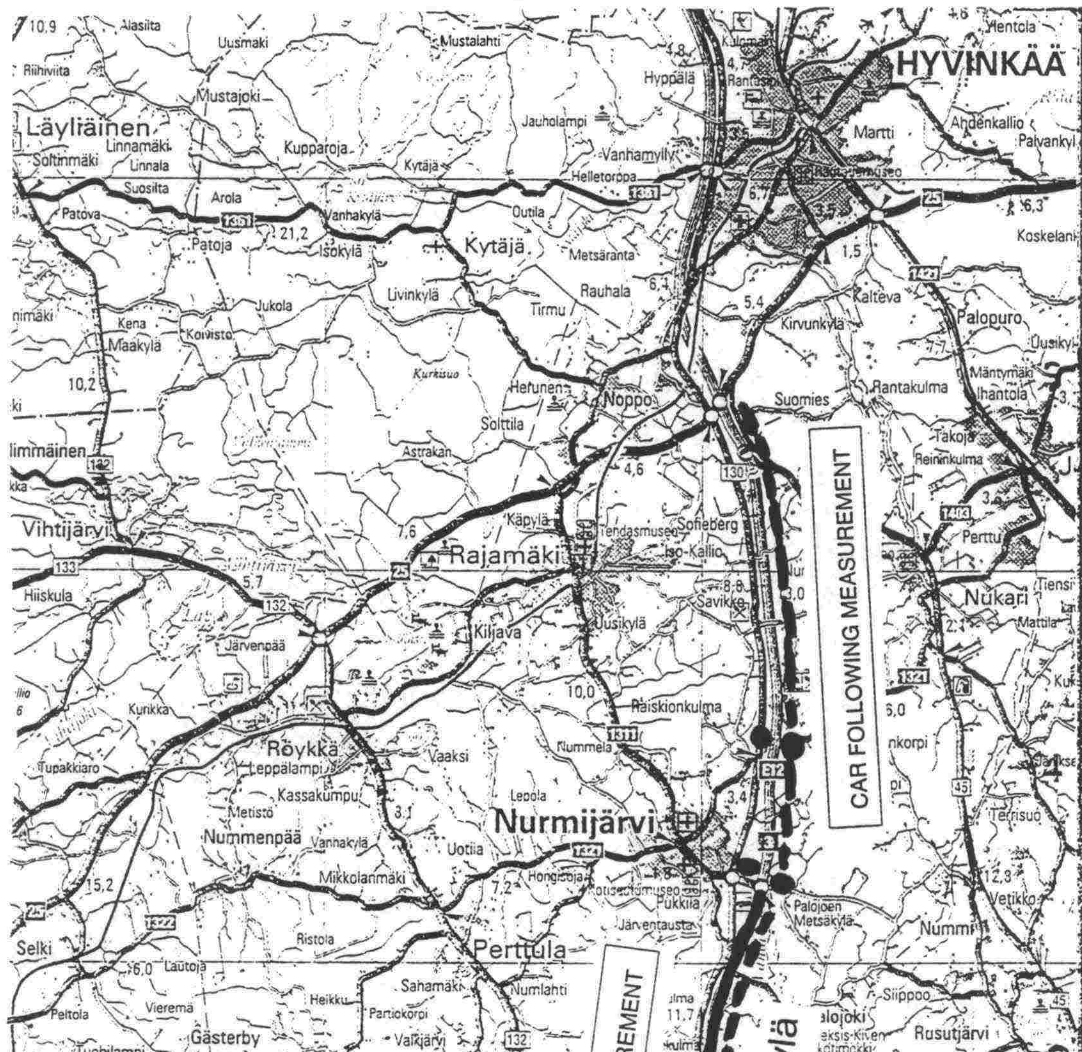

Figure A –3. Map of the measurement locations.

Appendix B –Acceleration rate of the following vehicle on Ring III

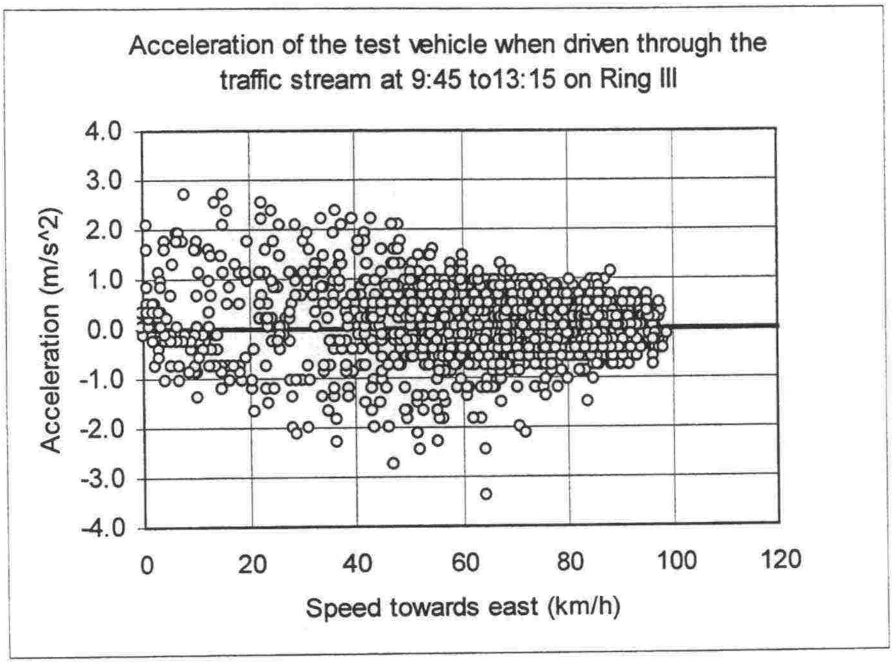

Figure B-1. Acceleration rate of the test vehicle on Ring Road III towards east.

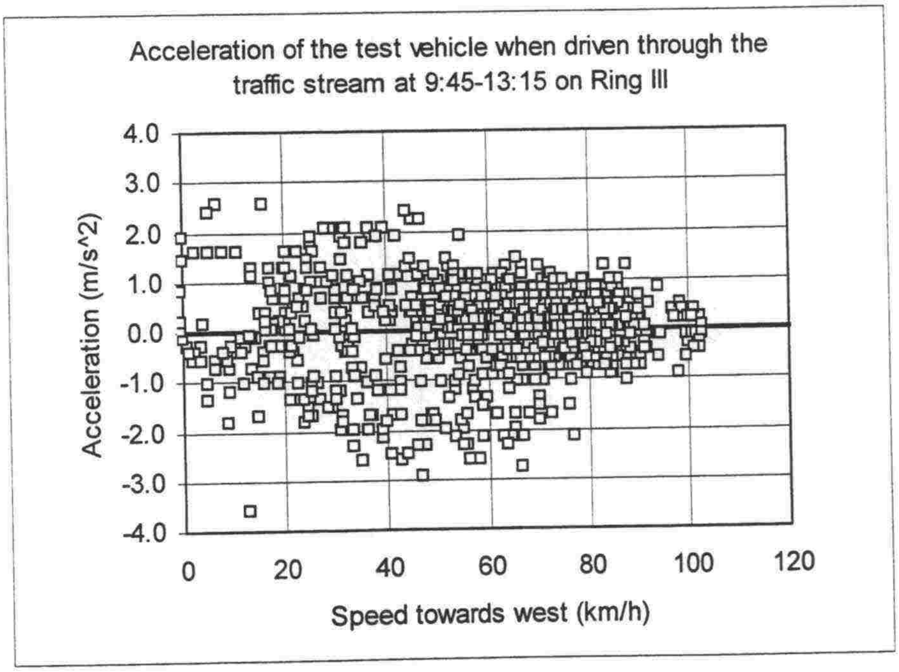

Figure B-2. Acceleration rate of the test vehicle on Ring Road III towards west.

Appendix C – Travel speed distributions on ramps, grades, and level sections

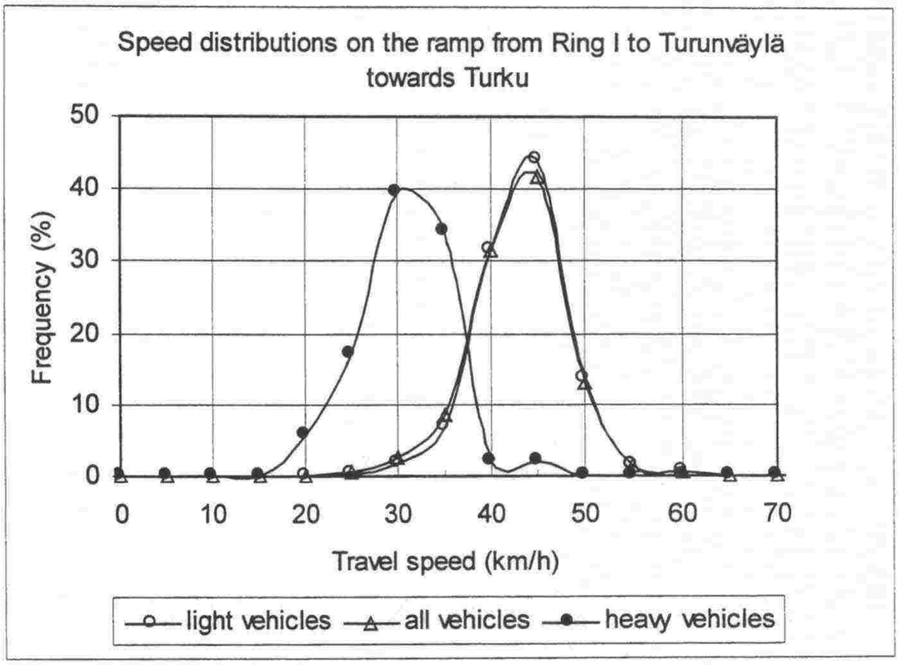

Figure C-1. Speed distributions on the ramp from Ring I to Turunväylä towards Turku.

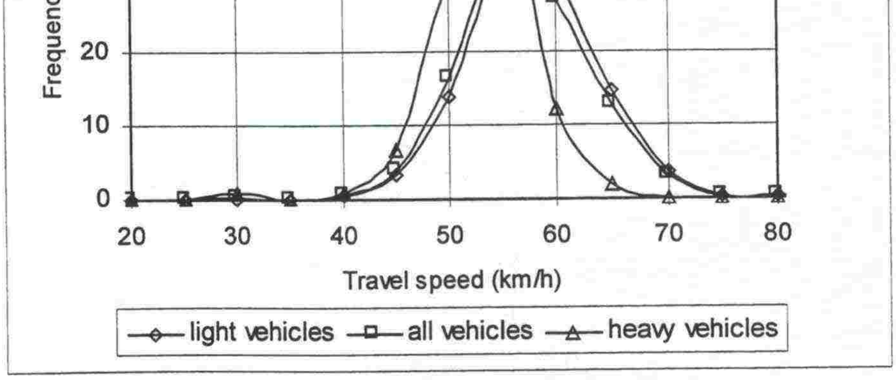

Figure C-2. Speed distributions on the ramp from Ring I to Länsiväylä towards Helsinki.

Appendix C – Travel speed distributions on ramps, grades, and level sections

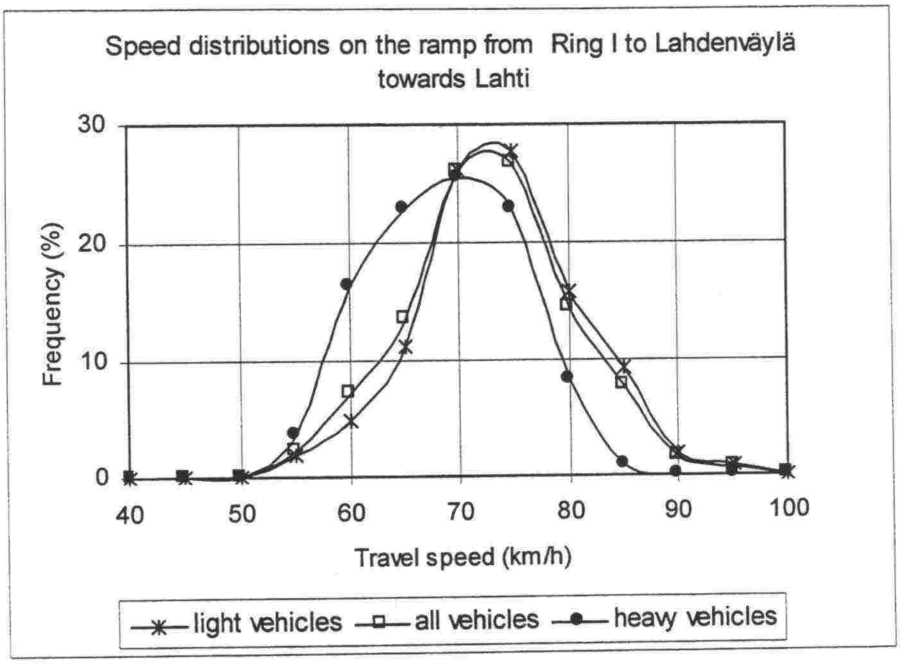

Figure C-3. Speed distributions on the ramp from Ring I to Lahdenväylä towards Lahti.

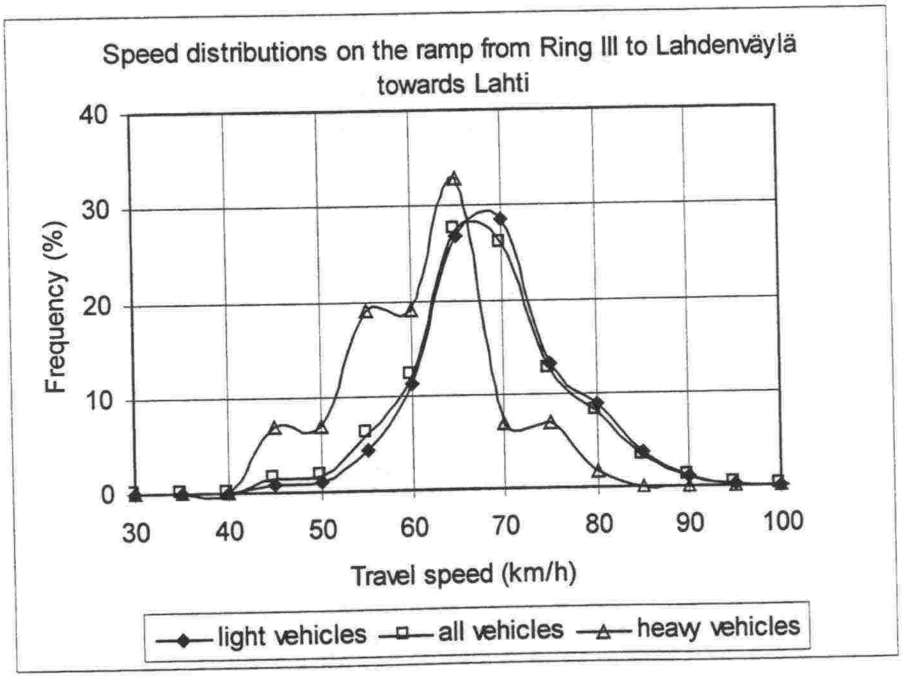

Figure C-4. Speed distributions on the ramp from Ring III to Lahdenväylä towards Lahti.

Appendix C – Travel speed distributions on ramps, grades, and level sections

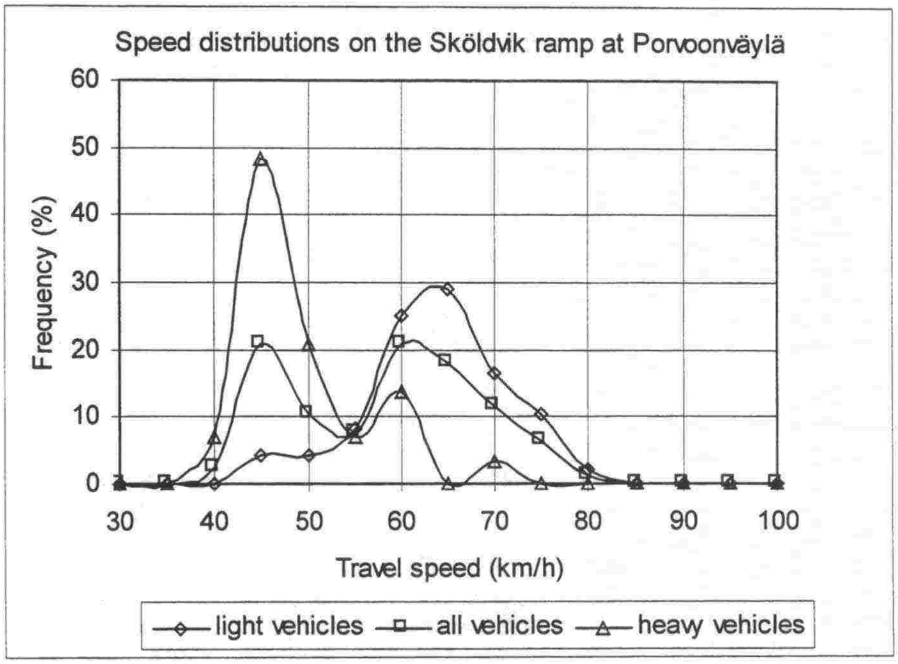

Figure C-5. Speed distributions on the Sköldvik ramp at Porvoonväylä.

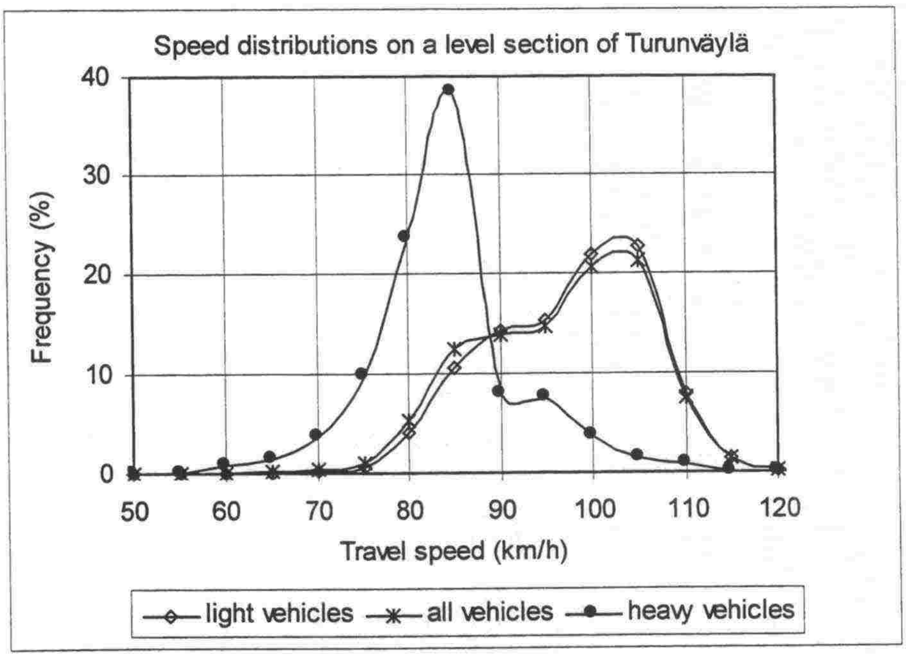

Figure C-6. Speed distributions on the level section before Tuomarila downgrade at Turunväylä towards Turku.

Appendix C – Travel speed distributions on ramps, grades, and level sections

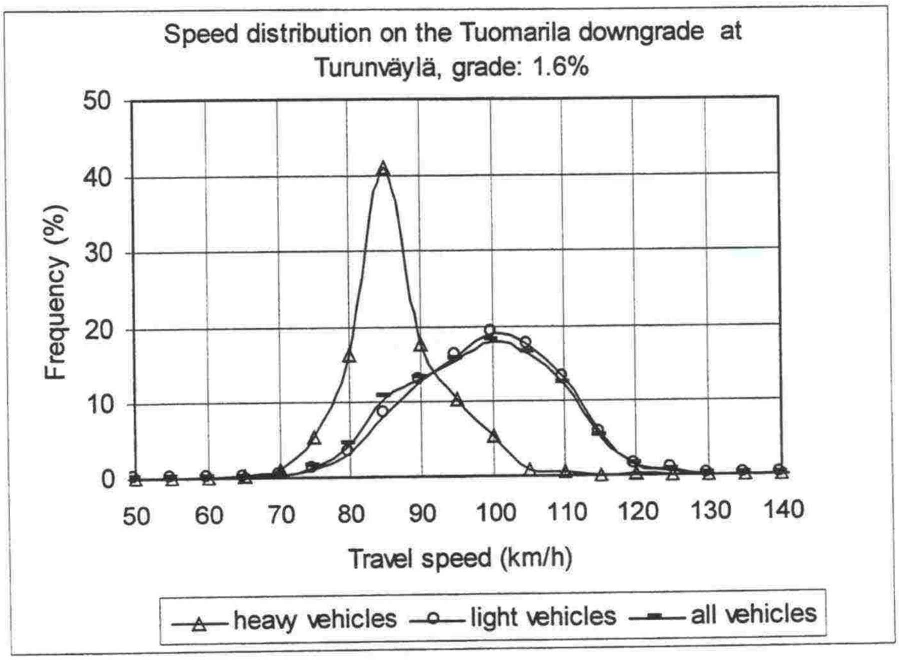

Figure C-7. Speed distributions on the Tuomarila downgrade at Turunväylä.

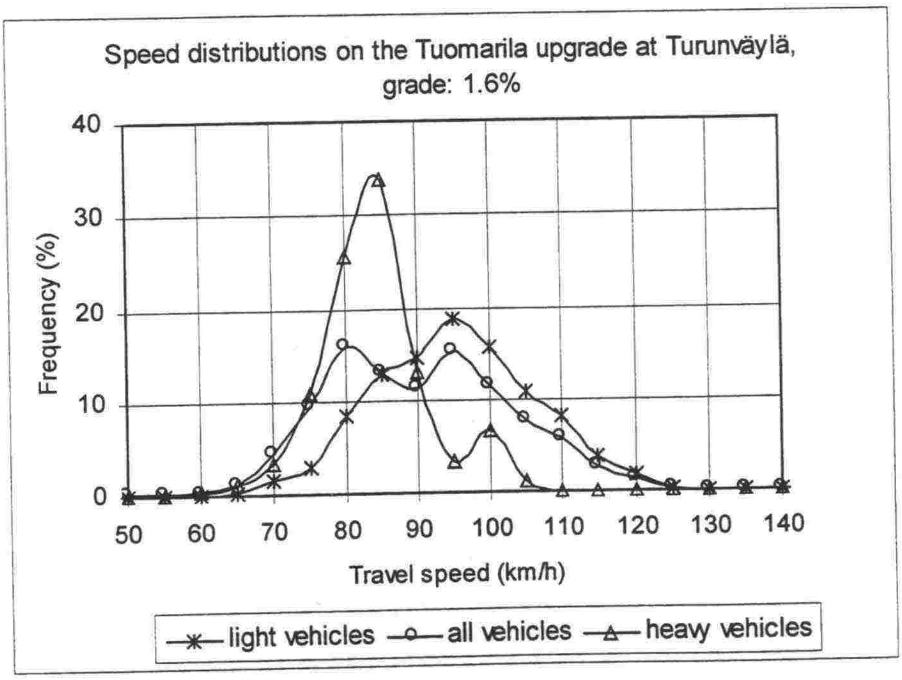

Figure C-8. Speed distributions on the Tuomarila upgrade at Turunväylä.

Appendix C – Travel speed distributions on ramps, grades, and level sections

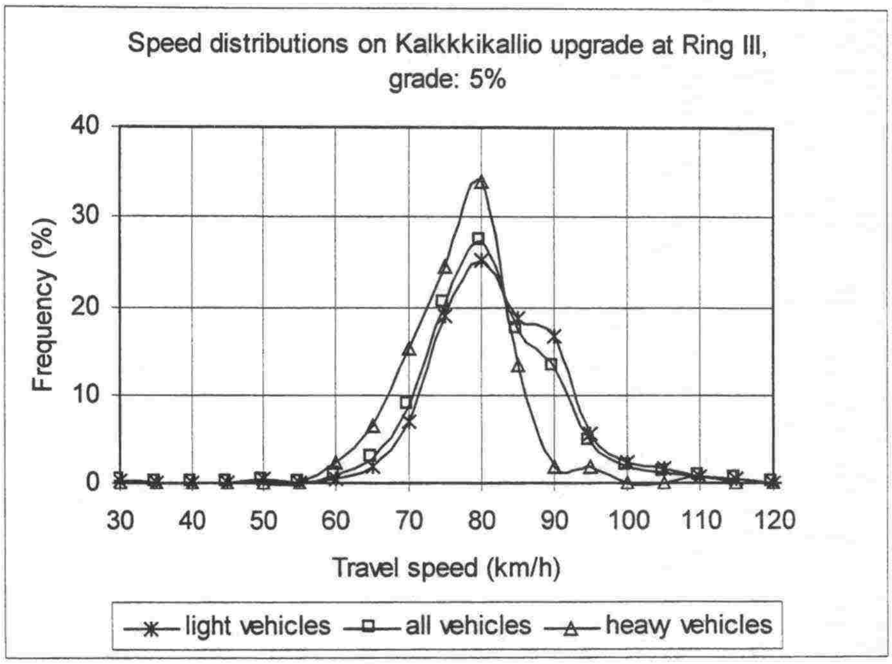

Figure C-9. Speed distributions on Kalkkikallio upgrade at Ring III.

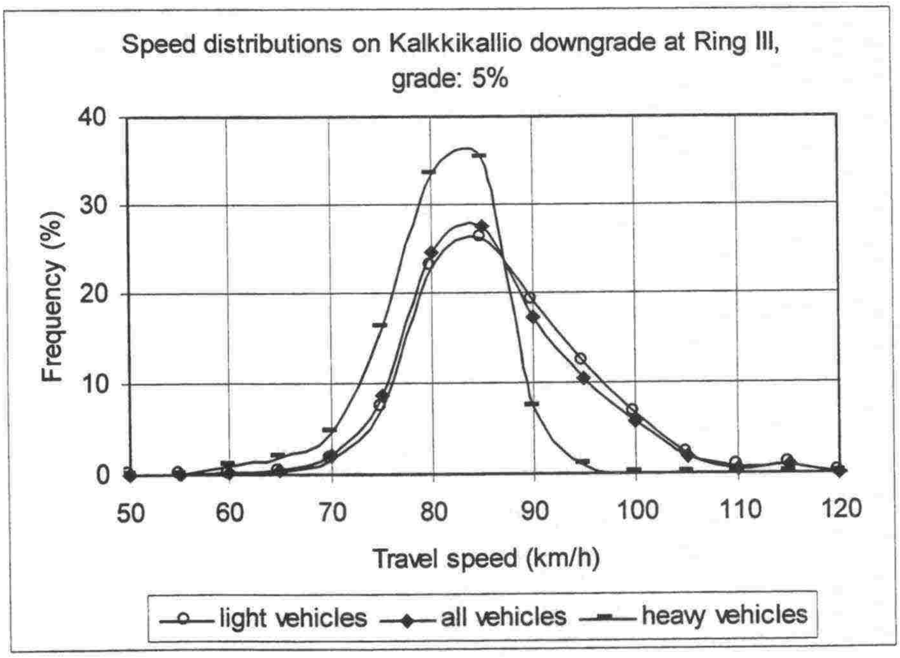

Figure C-10. Speed distributions on Kalkkikallio downgrade at Ring III.

Appendix C – Travel speed distributions on ramps, grades, and level sections

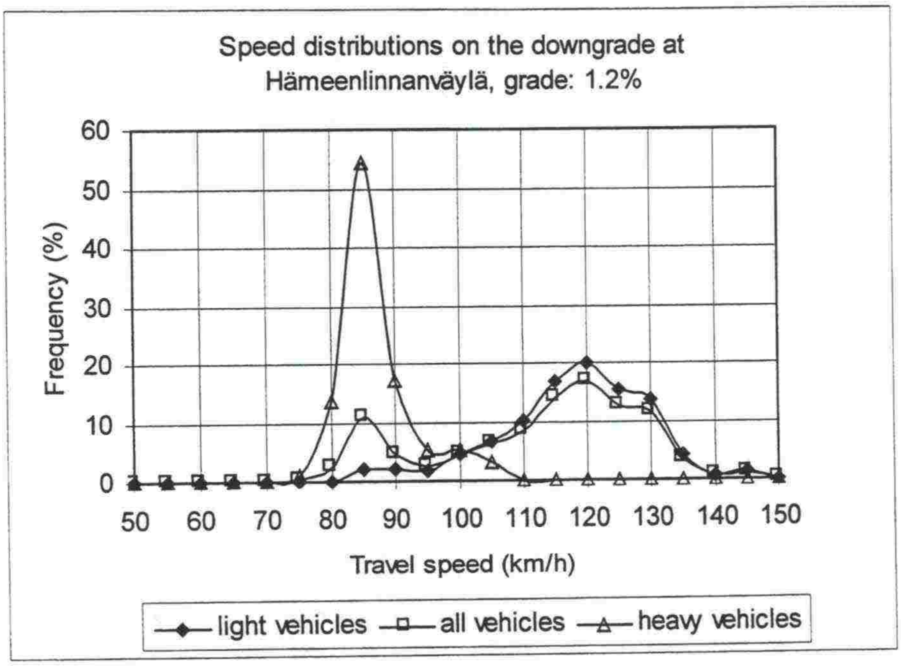

Figure C-11. Speed distributions on the downgrade at Hämeenlinnanväylä.

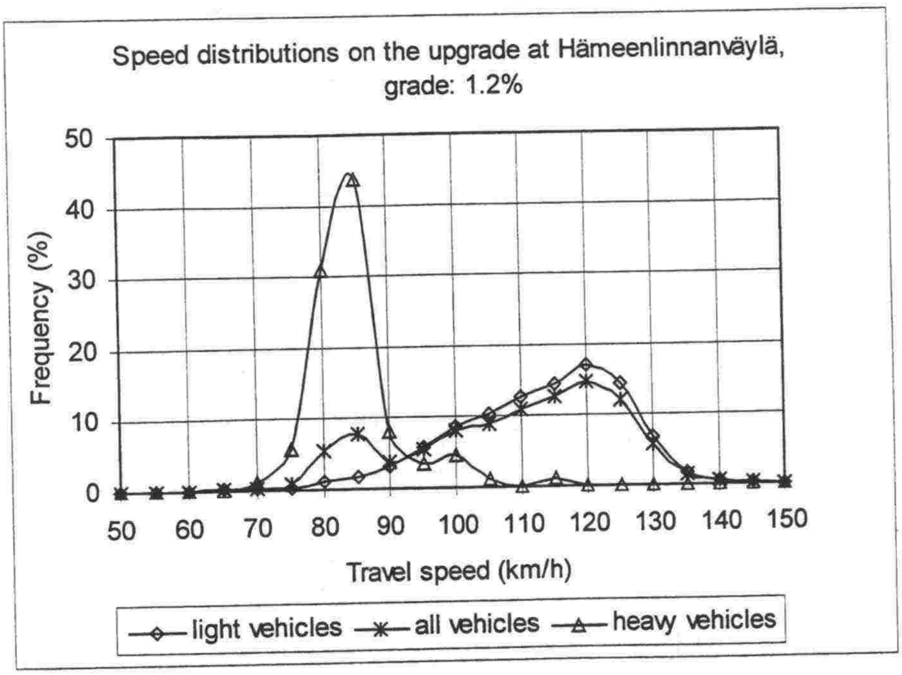

Figure C-12. Speed distributions on the upgrade at Hämeenlinnanväylä.

Appendix D— Configuration of the ramps, which were included in this study

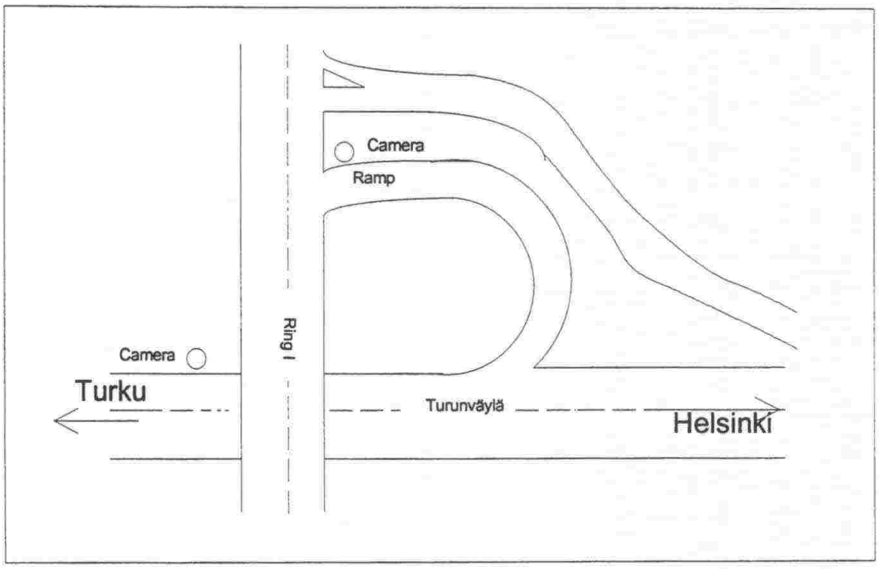

Figure D-1. Configuration of the ramp between Ring I and Turunväylä.

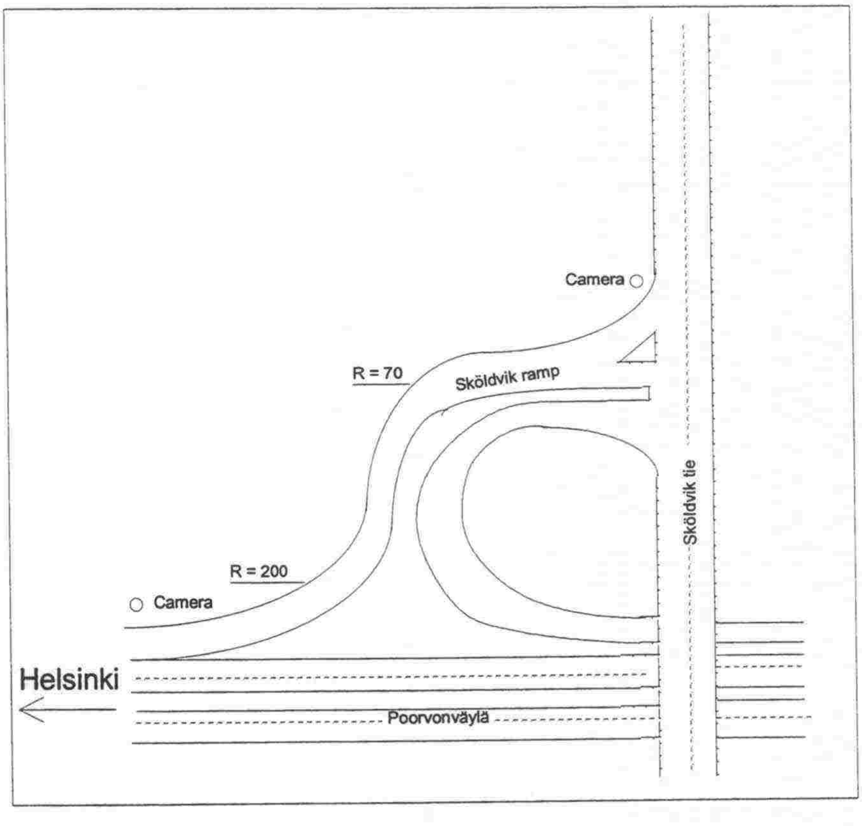

Figure D-2. Configuration of the ramp between Sköldviktie and Porvoonväylä.

Appendix D— Configuration of the ramps, which were included in this study

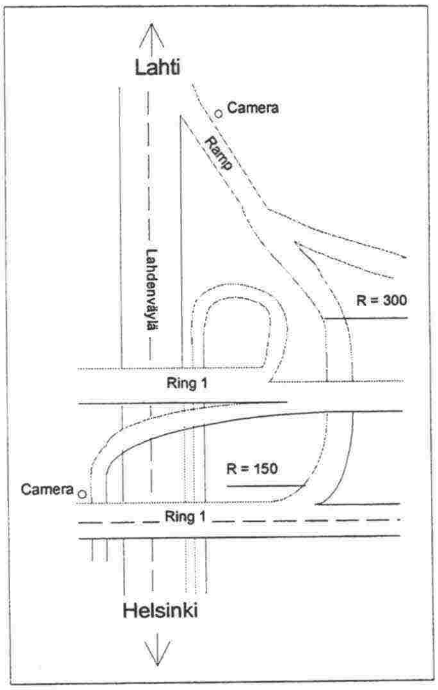

Figure D-3. Configuration of the ramp between Ring I and Lahdenväylä.

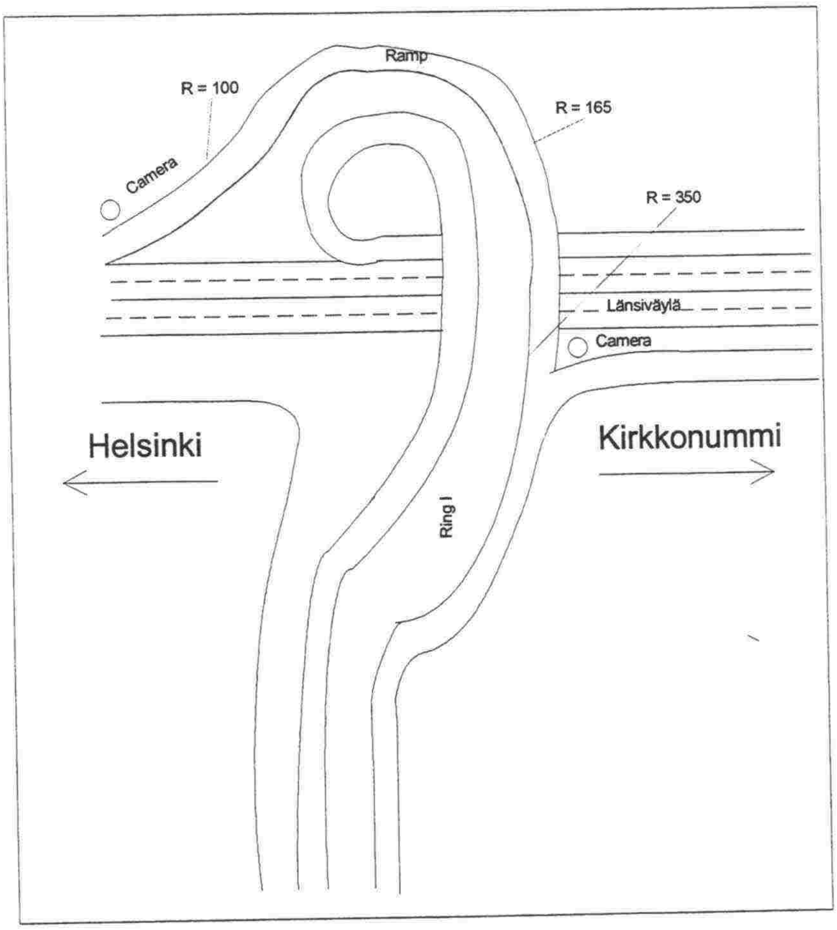

Figure D-4. Configuration oframp between Ring I and Länsiväylä.

Appendix D— Configuration of the ramps, which were included in this study

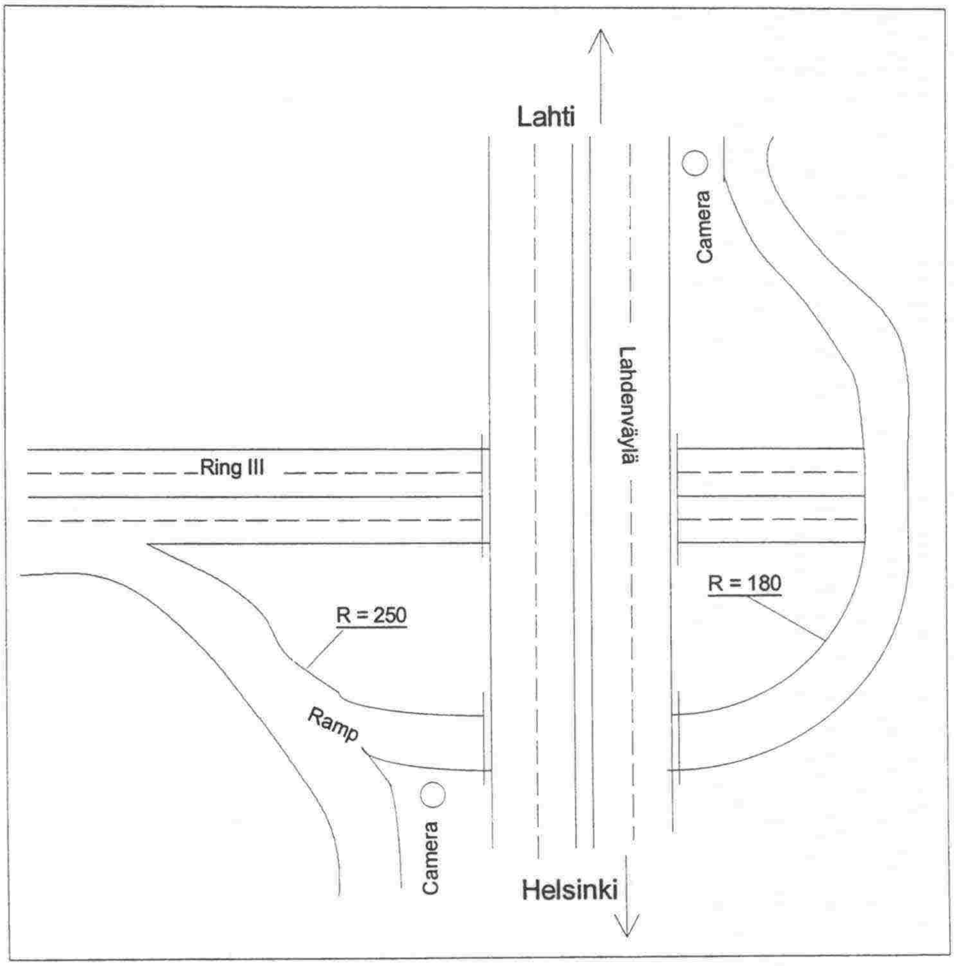

Figure D-5. Configuration of the ramp between Ring III and Lahdenväylä.

Appendix E – Speed-flow relationships on upgrades and downgrades

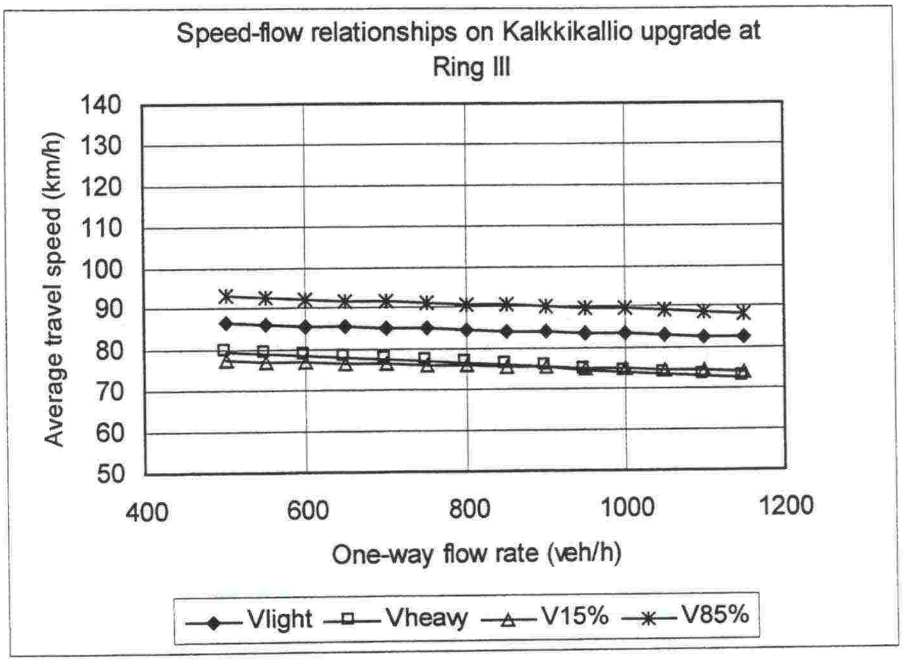

Figure E-1. Speed-flow relationships on Kalkkikallio upgrade at Ring III.

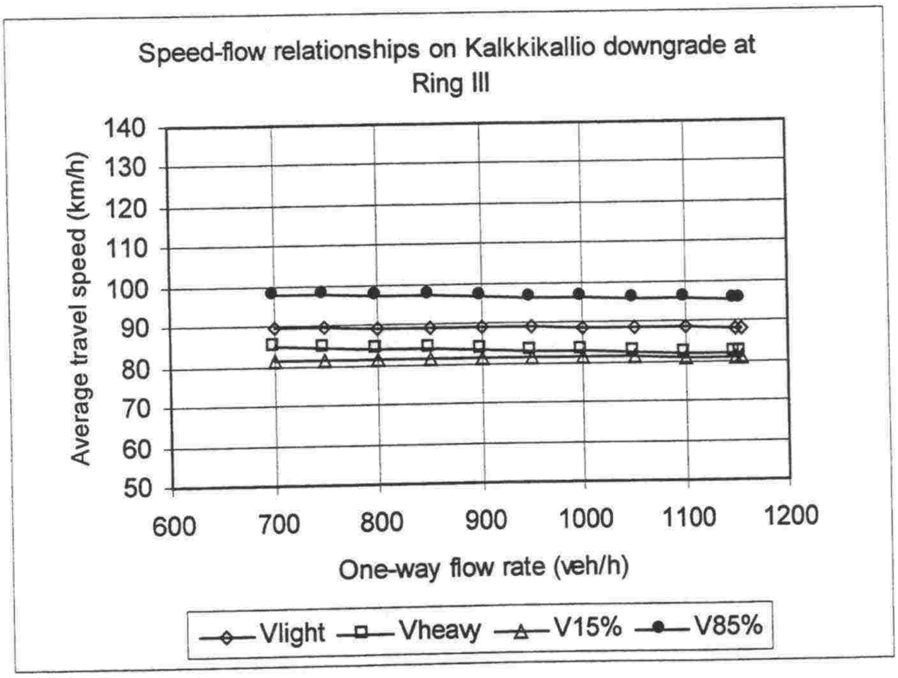

Figure E-2. Speed-flow relationships on Kalkkikallio downgrade at Ring III.

Appendix E – Speed-flow relationships on upgrades and downgrades

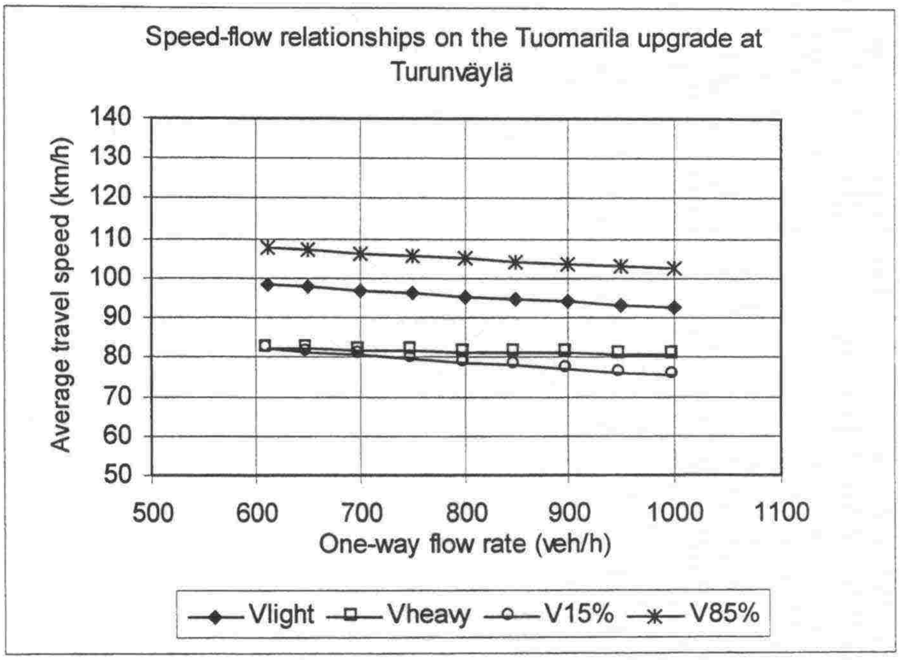

Figure E-3. Speed-flow relationships on the Tuomarila upgrade at Turunväylä.

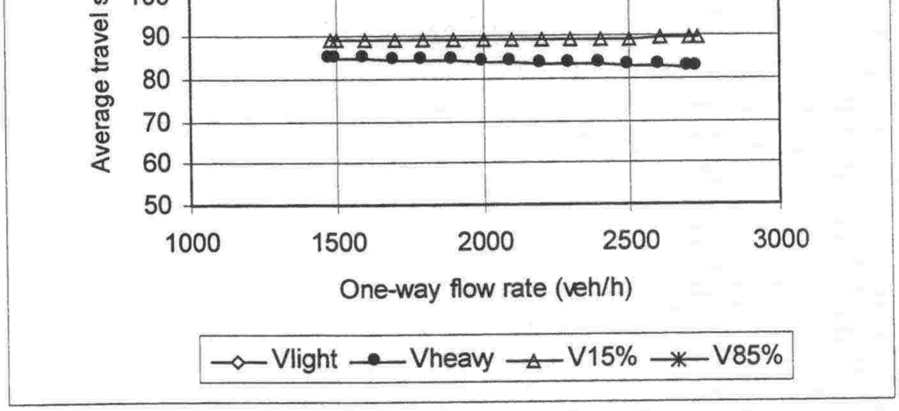

Figure E-4. Speed-flow relationships on the Tuomarila downgrade at Turunväylä

Appendix E – Speed-flow relationships on upgrades and downgrades

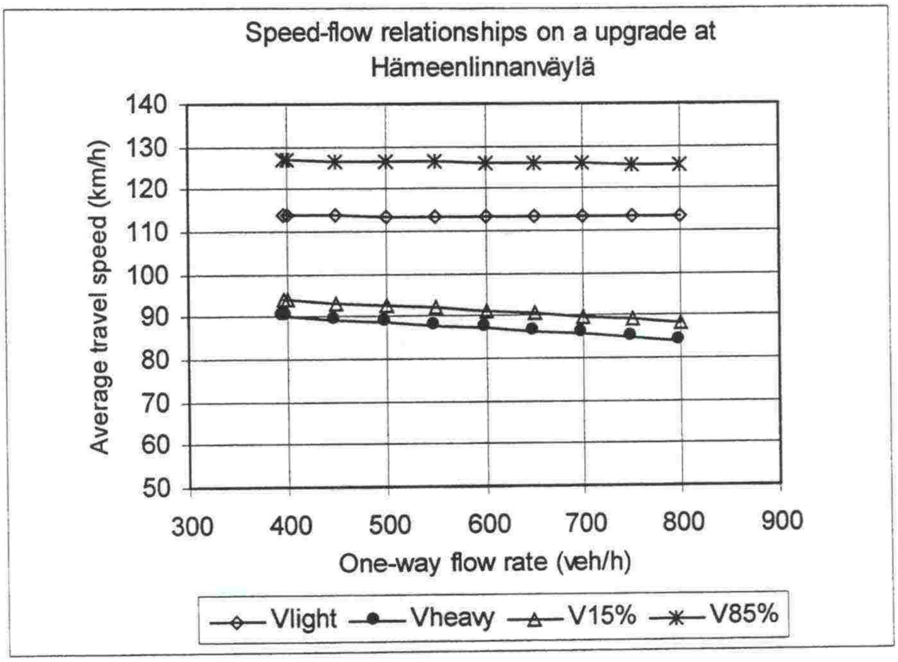

Figure E-5. Speed-flow relationship on an upgrade at Hämeenlinnanväylä.

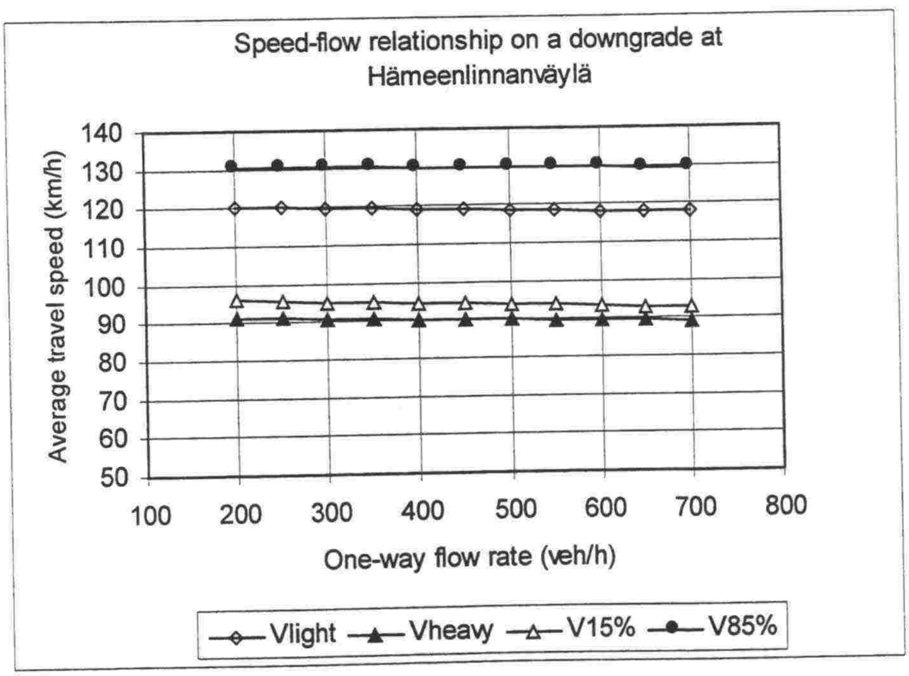

Figure E-6. Speed-flow relationships on a downgrade at Hämeenlinnanväylä.

Appendix F – The LAM sites used in this study and the data collection dates and times

Table F-1. The LAM sites, data collection dates and times.

LAM sites	Name	Road No.	Direction 1	Direction 2	Day, Month, Year	Time	Speed limit
101	HANA-SAARI	Kt51	Espoo	Helsinki	270897 280897 040997	6 a.m.-20 p.m.	80
102	SOUKKA	Kt51	Kirkkonummi	Helsinki	270897 280897 040997	6 a.m.-20 p.m.	100
104	PALO-JÄRVI	Vt1	Turku	Helsinki	220897 270897	6 a.m.-20 p.m.	120
107	KAIVOK-SELA	Vt3	Hämeenlinna	Helsinki	280897 020997 030997 040997 050997 100997 120997 250997	6 a.m.-20 p.m.	80
108	KARHUN-KORPI	Vt3	Hämeenlinna	Helsinki	280897 020997 030997 040997 050997 100997 120997 250997	6 a.m.-20 p.m.	120
109	JAKO-MÄKI	Vt4	Mäntsälä	Helsinki	210897 260897 270897 280897 040997	6 a.m.-20 p.m.	100
112	TREKSILÄ	Vt7	Porvoo	Helsinki	260897		120
128	VUOTILA	Kt50 (Ring Road III)	Vantaa	Kirkko-nummi	250897 180997 030997 040997 290997	6 a.m.-20 p.m.	80
131	TAM-MISTO	Kt45	Tuusula	Helsinki	040997	6 a.m.-20 p.m.	100
137	KEIMOLA	Vt3	Hämeenlinna	Helsinki	280897 020997 030997 040997 050997 100997 120997 250997	6 a.m.-20 p.m.	120
139	NUPURI	Vt1	Turku	Helsinki	220897 270897 040997	06:00-20:00	120

Appendix F – The LAM sites used in this study and the data collection dates and times

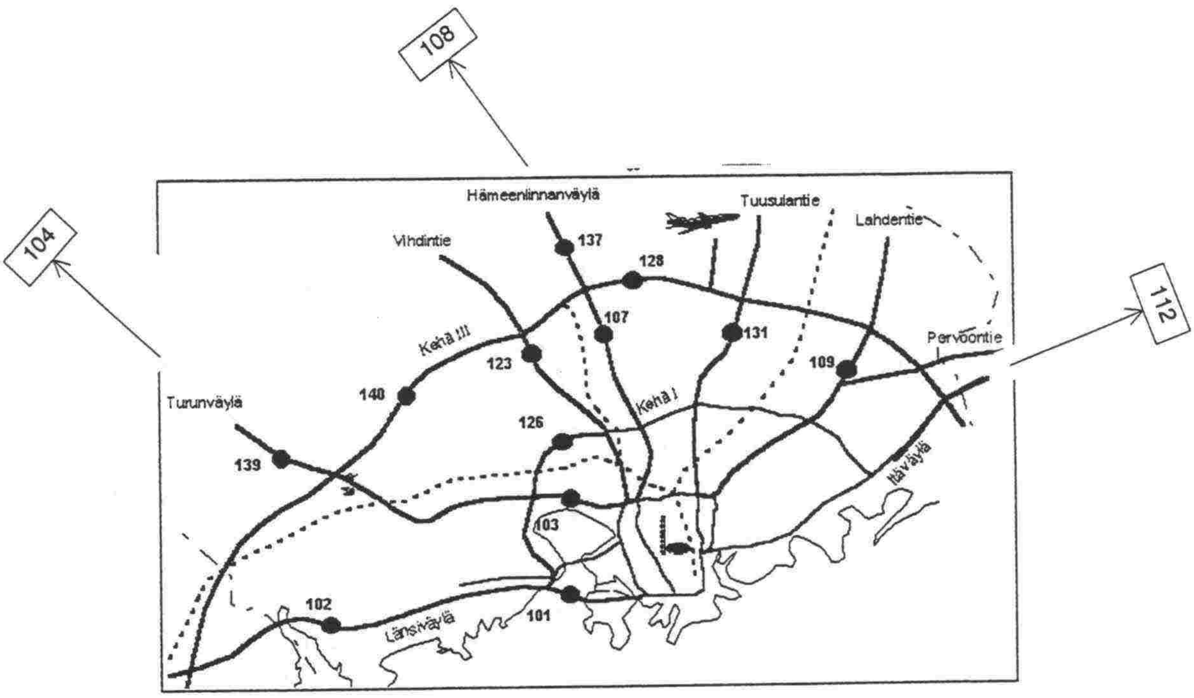

Figure F-1. Map of the LAM sites.

Appendix G – Space mean speed as a function of flow rate on freeways, regression coefficients

Table G-1. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Länsiväylä (LAM 101) towards Helsinki. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significancy of intercept	Statistical significancy of coefficient
V_{all}	Basic	95.64	-0.0101	0.48	Yes	Yes
V_{free}	Basic	94.36	-0.0079	0.33	Yes	Yes
$V_{constraint}$	Basic	95.26	-0.0100	0.47	Yes	Yes
V_{light}	Basic	96.13	-0.0105	0.50	Yes	Yes
V_{heavy}	Basic	91.75	-0.0092	0.06	Yes	Yes
V_{all}	Passing	97.24	-0.0056	0.70	Yes	Yes
V_{free}	Passing	96.83	-0.0027	0.32	Yes	Yes
$V_{constraint}$	Passing	96.41	-0.0053	0.59	Yes	Yes
V_{light}	Passing	97.33	-0.0056	0.71	Yes	Yes
V_{heavy}	Passing	91.25	-0.025	0.03	Yes	No
V_{all}	Both	91.41	-0.0027	0.47	Yes	Yes
V_{free}	Both	95.04	-0.0029	0.29	Yes	Yes
$V_{constraint}$	Both	90.77	-0.0029	0.42	Yes	Yes
V_{light}	Both	91.81	-0.0028	0.49	Yes	Yes
V_{heavy}	Both	89.60	-0.0044	0.09	Yes	Yes
V_{all}	Bus	84.71	-0.0168	0.18	Yes	Yes
V_{free}	Bus	84.62	-0.0116	0.02	Yes	Yes
$V_{constraint}$	Bus	81.14	-0.0045	0.01	Yes	No
V_{light}	Bus	90.83	-0.0284	0.36	Yes	Yes
V_{heavy}	Bus	80.90	-0.0199	0.24	Yes	Yes

Appendix G – Space mean speed as a function of flow rate on freeways, regression coefficients

Table G-2. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h on Länsiväylä (LAM 102) towards Helsinki. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	94.00	0.0035	0.10	Yes	No
V_{free}	Basic	92.92	0.0057	0.17	Yes	Yes
$V_{constraint}$	Basic	95.28	0.0013	0.01	Yes	No
V_{light}	Basic	96.40	0.0016	0.03	Yes	No
V_{heavy}	Basic	81.97	0.0036	0.05	Yes	No
V_{all}	Passing	106.97	0.0067	0.04	Yes	No
V_{free}	Passing	107.23	0.0076	0.05	Yes	No
$V_{constraint}$	Passing	103.43	0.0186	0.02	Yes	No
V_{light}	Passing	107.34	0.0057	0.03	Yes	No
V_{heavy}	Passing	91.15	0.0284	0.12	Yes	No
V_{all}	Both	94.79	0.0046	0.36	Yes	Yes
V_{free}	Both	93.90	0.0073	0.47	Yes	Yes
$V_{constraint}$	Both	94.97	0.0034	0.17	Yes	Yes
V_{light}	Both	96.79	0.0036	0.35	Yes	Yes
V_{heavy}	Both	82.33	0.0015	0.05	Yes	No

Table G-3. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Turunväylä (LAM 104) towards Turku. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	105.51	-0.0024	0.12	Yes	Yes
V_{free}	Basic	105.91	-0.0035	0.10	Yes	No
$V_{constraint}$	Basic	103.93	-0.0012	0.01	Yes	No
V_{light}	Basic	106.38	-0.0017	0.04	Yes	No
V_{heavy}	Basic	89.19	-0.0017	0.02	Yes	No
V_{all}	Passing	121.25	-0.0039	0.25	Yes	Yes
V_{free}	Passing	121.83	-0.0009	0.09	Yes	No
$V_{constraint}$	Passing	118.99	-0.0021	0.03	Yes	No
V_{light}	Passing	122.01	-0.0047	0.31	Yes	Yes
V_{heavy}	Passing	101.82	-0.0038	0.03	Yes	No
V_{all}	Both	117.27	-0.0054	0.31	Yes	Yes
V_{free}	Both	118.63	-0.0055	0.26	Yes	Yes
$V_{constraint}$	Both	116.90	-0.0054	0.27	Yes	Yes
V_{light}	Both	119.99	-0.0061	0.01	Yes	Yes
V_{heavy}	Both	95.63	-0.0048	0.27	Yes	Yes

Appendix G – Space mean speed as a function of flow rate on freeways, regression coefficients

Table G-4. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Turunväylä (LAM 139) towards Helsinki. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	102.19	-0.0016	0.01	Yes	No
V_{free}	Basic	101.18	-0.0009	0.01	Yes	No
$V_{constraint}$	Basic	101.34	-0.0002	0.01	Yes	No
V_{light}	Basic	106.60	-0.0026	0.03	Yes	No
V_{heavy}	Basic	86.36	-0.0003	0.01	Yes	No
V_{all}	Passing	118.93	-0.0020	0.03	Yes	No
V_{free}	Passing	119.20	-0.0006	0.01	Yes	No
$V_{constraint}$	Passing	118.10	-0.0026	0.03	Yes	No
V_{light}	Passing	119.09	-0.0021	0.05	Yes	Yes
V_{heavy}	Passing	102.77	-0.0016	0.01	Yes	No
V_{all}	Both	107.12	-0.0016	0.05	Yes	Yes
V_{free}	Both	107.88	-0.0011	0.02	Yes	No
$V_{constraint}$	Both	106.48	-0.0019	0.10	Yes	Yes
V_{light}	Both	109.46	-0.0006	0.01	Yes	No
V_{heavy}	Both	86.73	-0.0002	0.001	Yes	No

Table G-5. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Hämeenlinnanväylä (LAM 137) towards Helsinki. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	102.40	-0.0025	0.03	Yes	Yes
V_{free}	Basic	102.87	-0.0031	0.04	Yes	Yes
$V_{constraint}$	Basic	101.93	-0.0016	0.01	Yes	No
V_{light}	Basic	108.70	-0.0061	0.19	Yes	Yes
V_{heavy}	Basic	84.14	-0.0004	0.00	Yes	No
V_{all}	Passing	116.89	-0.0033	0.27	Yes	Yes
V_{free}	Passing	117.37	-0.0003	0.01	Yes	No
$V_{constraint}$	Passing	115.51	-0.0027	0.15	Yes	Yes
V_{light}	Passing	117.40	-0.0037	0.36	Yes	Yes
V_{heavy}	Passing	97.75	-0.0001	0.00	Yes	No
V_{all}	Both	105.35	-0.00003	0.00	Yes	No
V_{free}	Both	106.81	-0.0004	0.01	Yes	No
$V_{constraint}$	Both	104.67	-0.0002	0.01	Yes	Yes
V_{light}	Both	109.13	-0.0005	0.02	Yes	Yes
V_{heavy}	Both	84.63	-0.0001	0.00	Yes	No

Appendix G – Space mean speed as a function of flow rate on freeways, regression coefficients

Table G-6. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Hämeenlinnanväylä (LAM 137) towards Hämeenlinna. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	106.72	-0.0026	0.10	Yes	Yes
V_{free}	Basic	105.07	-0.00001	0.00	Yes	No
$V_{constraint}$	Basic	107.57	-0.0034	0.12	Yes	Yes
V_{light}	Basic	113.30	-0.0064	0.46	Yes	Yes
V_{heavy}	Basic	91.16	-0.0022	0.08	Yes	Yes
V_{all}	Passing	121.80	-0.0023	0.27	Yes	Yes
V_{free}	Passing	122.44	-0.0017	0.07	Yes	Yes
$V_{constraint}$	Passing	121.08	-0.0021	0.10	Yes	Yes
V_{light}	Passing	122.01	-0.0025	0.24	Yes	Yes
V_{heavy}	Passing	103.69	-0.0006	0.00	Yes	No
V_{all}	Both	109.90	-0.0007	0.04	Yes	No
V_{free}	Both	110.38	-0.0002	0.01	Yes	No
$V_{constraint}$	Both	109.28	-0.0007	0.04	Yes	No
V_{light}	Both	113.16	-0.0003	0.01	Yes	No
V_{heavy}	Both	90.68	-0.0004	0.02	Yes	No

Table G-7. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Hämeenlinnanväylä (LAM 108) towards Helsinki. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	107.60	0.0008	0.01	Yes	No
V_{free}	Basic	108.10	-0.0011	0.01	Yes	No
$V_{constraint}$	Basic	107.66	0.0016	0.01	Yes	No
V_{light}	Basic	114.61	-0.0045	0.02	Yes	Yes
V_{heavy}	Basic	88.50	-0.0014	0.00	Yes	No
V_{all}	passing	123.12	-0.0140	0.06	Yes	Yes
V_{free}	passing	123.49	-0.0147	0.05	Yes	Yes
$V_{constraint}$	passing	121.13	-0.0078	0.01	Yes	No
V_{light}	passing	123.29	-0.0128	0.05	Yes	Yes
V_{heavy}	passing	102.18	-0.0481	0.08	Yes	Yes
V_{all}	Both	109.50	0.0015	0.01	Yes	No
V_{free}	Both	110.88	0.0002	0.00	Yes	No
$V_{constraint}$	Both	108.41	0.0027	0.02	Yes	Yes
V_{light}	Both	115.20	-0.0012	0.01	Yes	No
V_{heavy}	Both	89.40	-0.0028	0.01	Yes	No

Appendix G – Space mean speed as a function of flow rate on freeways, regression coefficients

Table G-8. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Hämeenlinnanväylä (LAM 107) towards Helsinki. ***Model: $V_s = a + b \times q$***

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	86.12	-0.0032	0.14	Yes	Yes
V_{free}	Basic	88.33	-0.0055	0.18	Yes	Yes
$V_{constraint}$	Basic	85.67	-0.0028	0.11	Yes	Yes
V_{light}	Basic	86.37	-0.0029	0.12	Yes	Yes
V_{heavy}	Basic	86.11	-0.0071	0.19	Yes	Yes
V_{all}	Passing	94.37	-0.0029	0.27	Yes	Yes
V_{free}	Passing	94.31	-0.0005	0.02	Yes	Yes
$V_{constraint}$	Passing	93.18	-0.0020	0.10	Yes	Yes
V_{light}	Passing	94.62	-0.0030	0.30	Yes	Yes
V_{heavy}	Passing	89.70	-0.0014	0.02	Yes	Yes
V_{all}	Both	85.71	-0.0002	0.01	Yes	No
V_{free}	Both	87.87	-0.0003	0.01	Yes	No
$V_{constraint}$	Both	84.85	-0.0002	0.01	Yes	No
V_{light}	Both	86.30	-0.0001	0.00	Yes	No
V_{heavy}	Both	83.62	-0.0025	0.20	Yes	Yes

Table G-9. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Lahdenväylä (LAM 109) towards Helsinki. Model: ***$V_s = a + b \times q$***

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	103.01	-0.0055	0.38	Yes	Yes
V_{free}	Basic	102.66	-0.0053	0.36	Yes	Yes
$V_{constraint}$	Basic	101.83	-0.0034	0.14	Yes	Yes
V_{light}	Basic	105.95	-0.0068	0.53	Yes	Yes
V_{heavy}	Basic	88.54	-0.0002	0.01	Yes	No
V_{all}	Passing	112.79	-0.0043	0.48	Yes	Yes
V_{free}	Passing	112.56	-0.0019	0.12	Yes	Yes
$V_{constraint}$	Passing	112.04	-0.0040	0.36	Yes	Yes
V_{light}	Passing	112.95	-0.0044	0.50	Yes	Yes
V_{heavy}	Passing	100.78	-0.0014	0.01	Yes	No
V_{all}	Both	102.32	-0.0008	0.11	Yes	Yes
V_{free}	Both	103.91	-0.0001	0.01	Yes	No
$V_{constraint}$	Both	100.64	-0.0004	0.03	Yes	Yes
V_{light}	Both	104.62	-0.0013	0.27	Yes	Yes
V_{heavy}	Both	89.01	-0.0003	0.01	Yes	No

Appendix G – Space mean speed as a function of flow rate on freeways, regression coefficients

Table G-10. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Lahdenväylä (LAM 109) towards Mäntsälä. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	102.23	-0.0051	0.29	Yes	Yes
V_{free}	Basic	102.68	-0.0053	0.28	Yes	Yes
$V_{constraint}$	Basic	101.71	-0.0046	0.23	Yes	Yes
V_{light}	Basic	105.90	-0.0067	0.43	Yes	Yes
V_{heavy}	Basic	90.35	-0.0034	0.12	Yes	Yes
V_{all}	Passing	112.35	-0.0026	0.17	Yes	Yes
V_{free}	Passing	113.11	-0.0018	0.10	Yes	Yes
$V_{constraint}$	Passing	111.06	-0.0019	0.06	Yes	No
V_{light}	Passing	112.64	-0.0027	0.20	Yes	Yes
V_{heavy}	Passing	102.39	-0.0030	0.03	Yes	No
V_{all}	Both	102.33	-0.0005	0.04	Yes	No
V_{free}	Both	104.22	-0.0003	0.01	Yes	No
$V_{constraint}$	Both	100.78	-0.0002	0.01	Yes	No
V_{light}	Both	105.26	-0.0012	0.18	Yes	Yes
V_{heavy}	Both	89.69	-0.0013	0.09	Yes	Yes

Table G-11. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Porvoonväylä (LAM 112) towards Helsinki. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	100.50	0.0080	0.21	Yes	Yes
V_{free}	Basic	102.30	0.0059	0.10	Yes	No
$V_{constraint}$	Basic	99.99	0.0079	0.17	Yes	Yes
V_{light}	Basic	107.10	0.0035	0.07	Yes	No
V_{heavy}	Basic	82.86	-0.0068	0.23	Yes	Yes
V_{all}	Passing	118.96	0.0035	0.03	Yes	No
V_{free}	Passing	119.83	0.0015	0.01	Yes	No
$V_{constraint}$	Passing	119.12	0.0005	0.00	Yes	No
V_{light}	Passing	119.35	0.0035	0.04	Yes	No
V_{heavy}	Passing	96.17	-0.0099	0.01	Yes	No
V_{all}	Both	103.35	0.0069	0.45	Yes	Yes
V_{free}	Both	105.26	0.0042	0.15	Yes	Yes
$V_{constraint}$	Both	103.84	0.0060	0.22	Yes	Yes
V_{light}	Both	108.90	0.0044	0.36	Yes	Yes
V_{heavy}	Both	83.89	0.0037	0.22	Yes	Yes

Appendix G – Space mean speed as a function of flow rate on freeways, regression coefficients

Table G-12. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Tuusulanväylä (LAM 131) towards Helsinki. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	99.91	-0.0079	0.75	Yes	Yes
V_{free}	Basic	99.98	-0.0055	0.30	Yes	Yes
$V_{constraint}$	Basic	99.21	-0.0076	0.71	Yes	Yes
V_{light}	Basic	102.43	-0.0093	0.83	Yes	Yes
V_{heavy}	Basic	86.36	-0.0023	0.11	Yes	No
V_{all}	Passing	106.60	-0.0048	0.76	Yes	Yes
V_{free}	Passing	105.68	-0.0007	0.05	Yes	No
$V_{constraint}$	Passing	104.50	-0.0031	0.30	Yes	Yes
V_{light}	Passing	106.72	-0.0049	0.77	Yes	Yes
V_{heavy}	Passing	96.27	-0.0028	0.01	Yes	No
V_{all}	Both	98.18	-0.0016	0.53	Yes	Yes
V_{free}	Both	99.76	-0.0006	0.07	Yes	No
$V_{constraint}$	Both	96.27	-0.0011	0.31	Yes	Yes
V_{light}	Both	99.96	-0.0020	0.65	Yes	Yes
V_{heavy}	Both	85.42	-0.0005	0.04	Yes	No

Table G-13. Space mean speed (V_s, km/h) as a function of flow rate (q, veh/h) on Tuusulanväylä (LAM 131) towards Tuusula. ***Model:*** $V_s = a + b \times q$

Speed type	Lane type	Intercept a	Coeffic. b	R^2	Statistical significance of intercept	Statistical significance of coefficient
V_{all}	Basic	98.64	-0.0035	0.18	Yes	Yes
V_{free}	Basic	97.53	-0.0017	0.02	Yes	No
$V_{constraint}$	Basic	98.39	-0.0035	0.17	Yes	Yes
V_{light}	Basic	101.13	-0.0050	0.36	Yes	Yes
V_{heavy}	Basic	89.29	-0.0016	0.04	Yes	No
V_{all}	Passing	109.74	-0.0028	0.22	Yes	Yes
V_{free}	Passing	110.04	-0.0018	0.09	Yes	No
$V_{constraint}$	Passing	109.12	-0.0025	0.15	Yes	Yes
V_{light}	Passing	109.73	-0.0028	0.23	Yes	Yes
V_{heavy}	Passing	103.02	-0.0027	0.02	Yes	No
V_{all}	Both	99.85	-0.0005	0.02	Yes	No
V_{free}	Both	102.35	-0.0008	0.04	Yes	No
$V_{constraint}$	Both	99.68	-0.0009	0.07	Yes	No
V_{light}	Both	100.84	-0.0003	0.01	Yes	No
V_{heavy}	Both	89.95	-0.0014	0.17	Yes	Yes

Appendix H— Space mean speed as a function of flow rate on freeways, regression lines

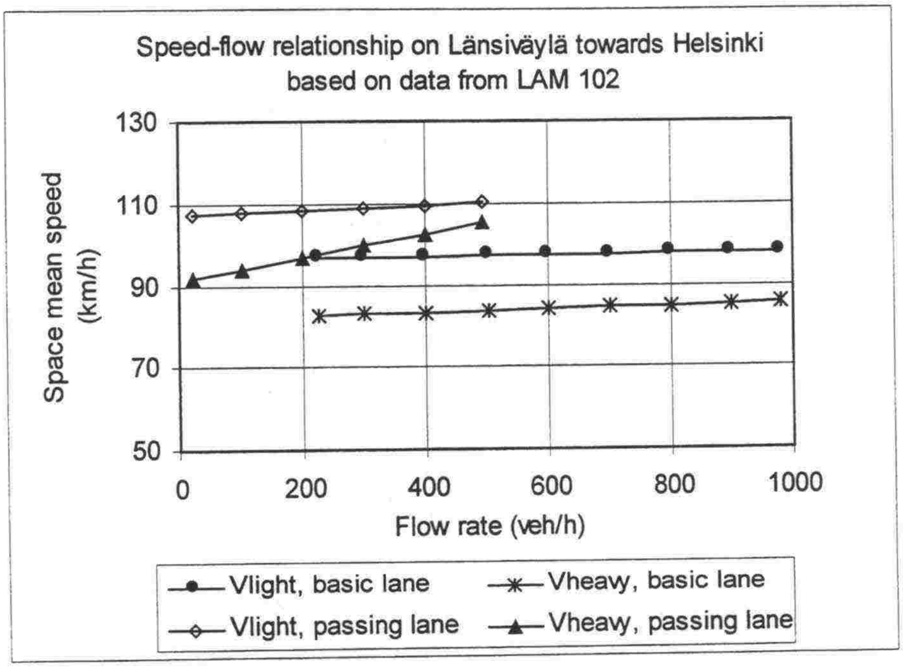

Figure H-1. Speed-flow relationships on Länsiväylä towards Helsinki.

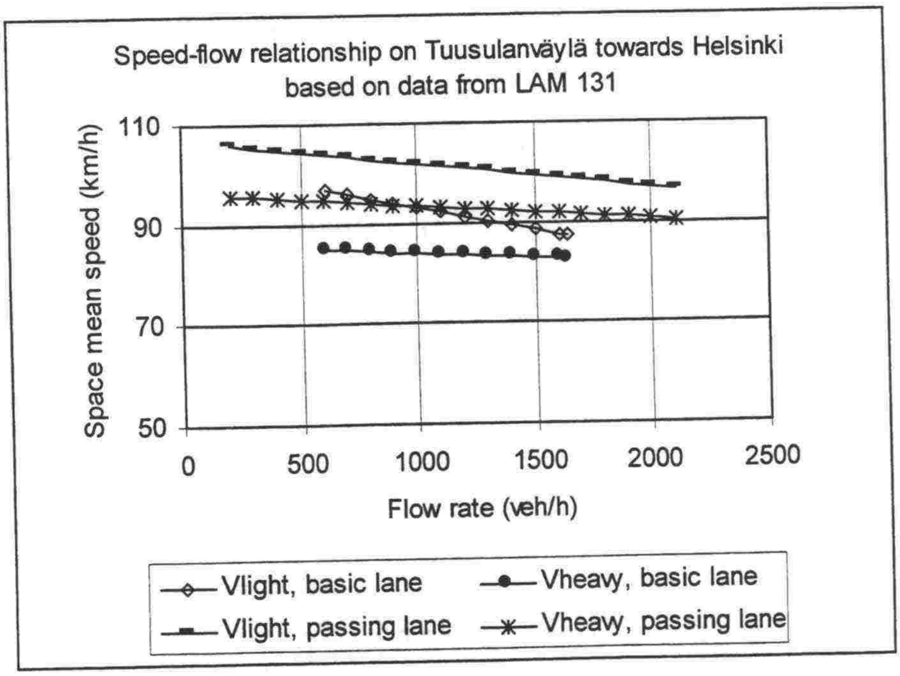

Figure H-2. Speed-flow relationships on Tuusulanväylä towards Helsinki.

Appendix H— Space mean speed as a function of flow rate on freeways, regression lines

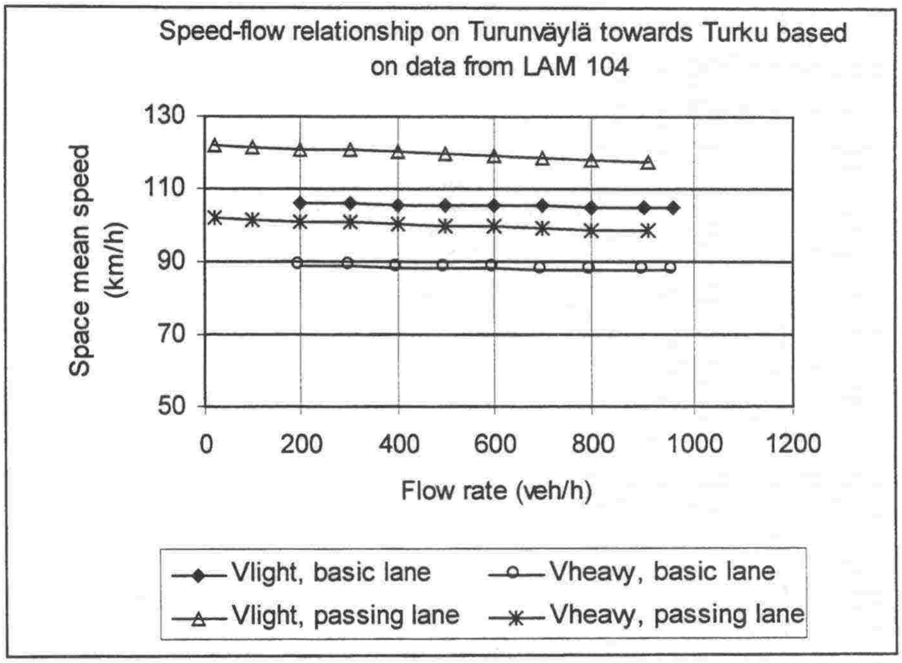

Figure H-3. Speed-flow relationships on Turunväylä towards Turku.

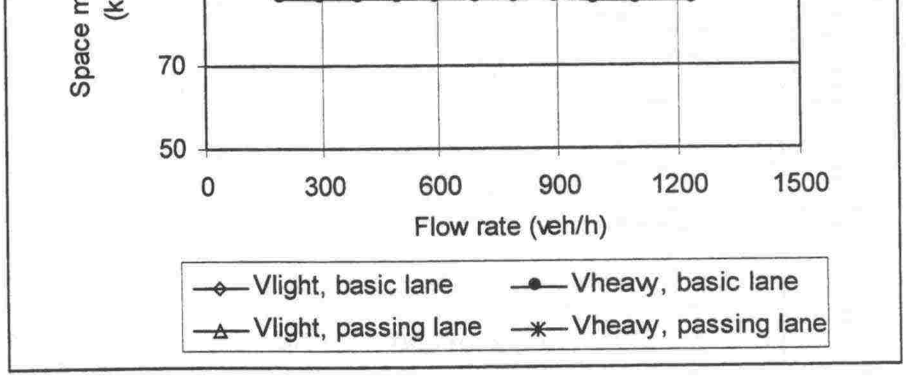

Figure H-4. Speed-flow relationships on Turunväylä towards Helsinki.

Appendix H— Space mean speed as a function of flow rate on freeways, regression lines

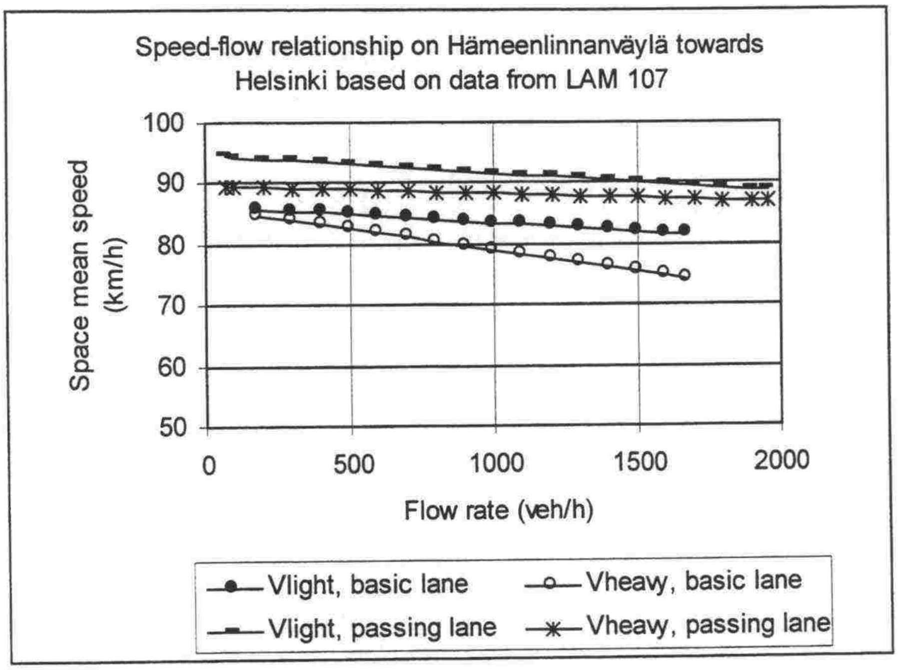

Figure H-5. Speed-flow relationships on Hämeenlinnanväylä towards Helsinki.

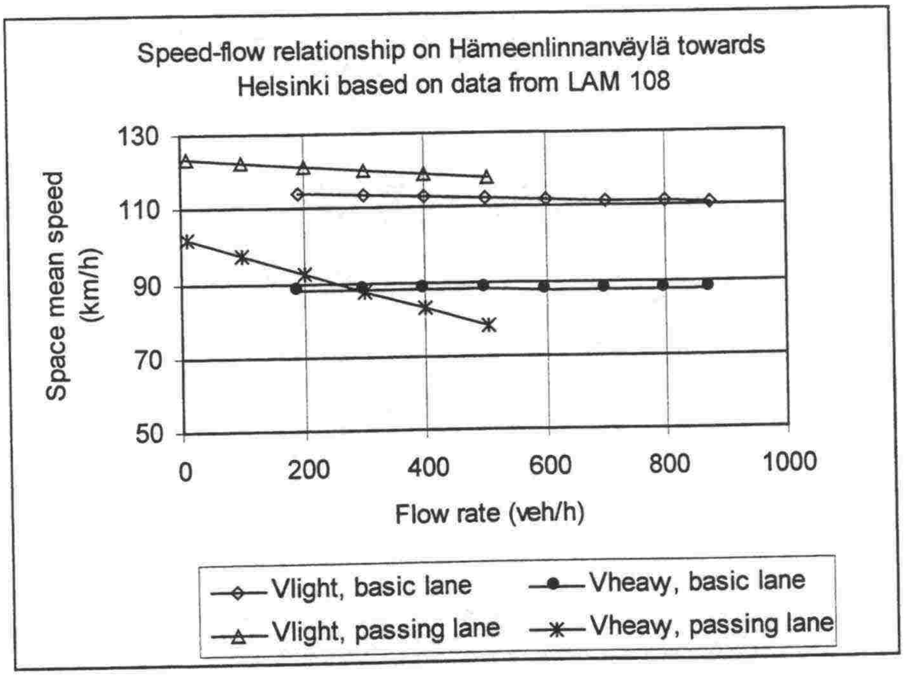

Figure H-6. Speed-flow relationships on Hämeenlinnanväylä towards Helsinki.

Appendix H— Space mean speed as a function of flow rate on freeways, regression lines

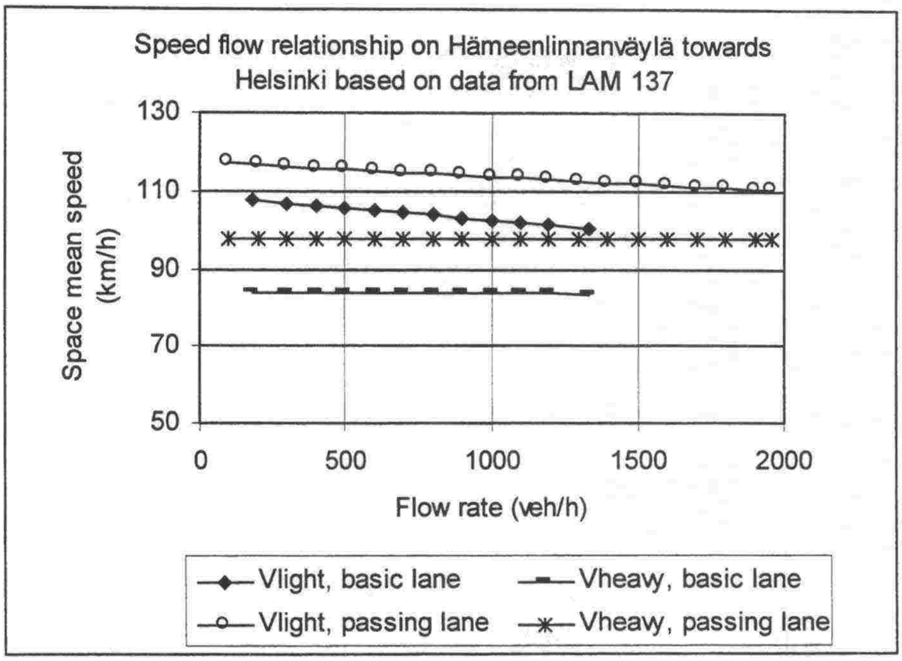

Figure H-7. Speed-flow relationships on Hämeenlinnanväylä towards Helsinki.

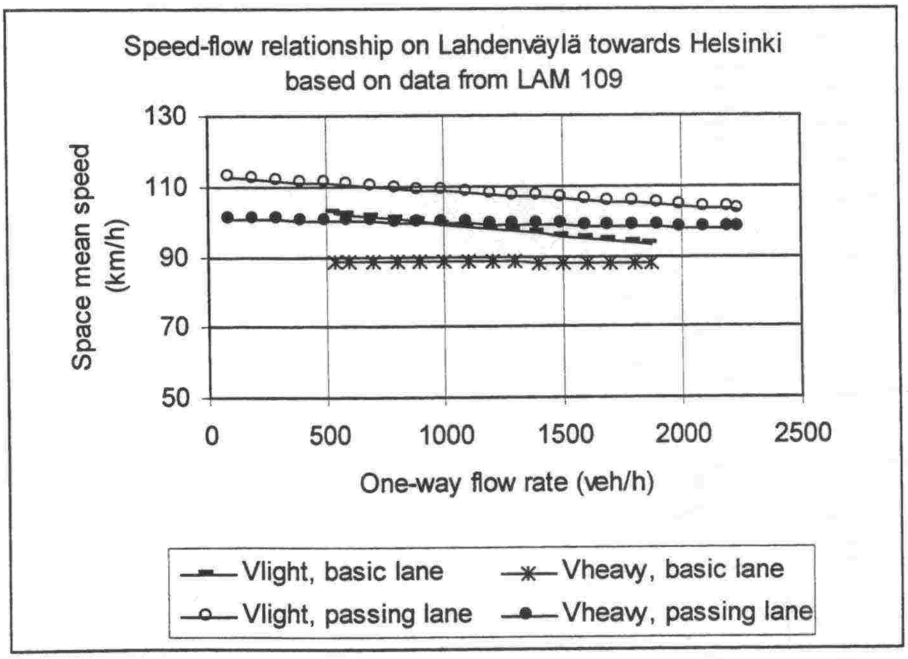

Figure H-8. Speed-flow relationships on Lahdenväylä towards Helsinki.

Appendix H— Space mean speed as a function of flow rate on freeways, regression lines

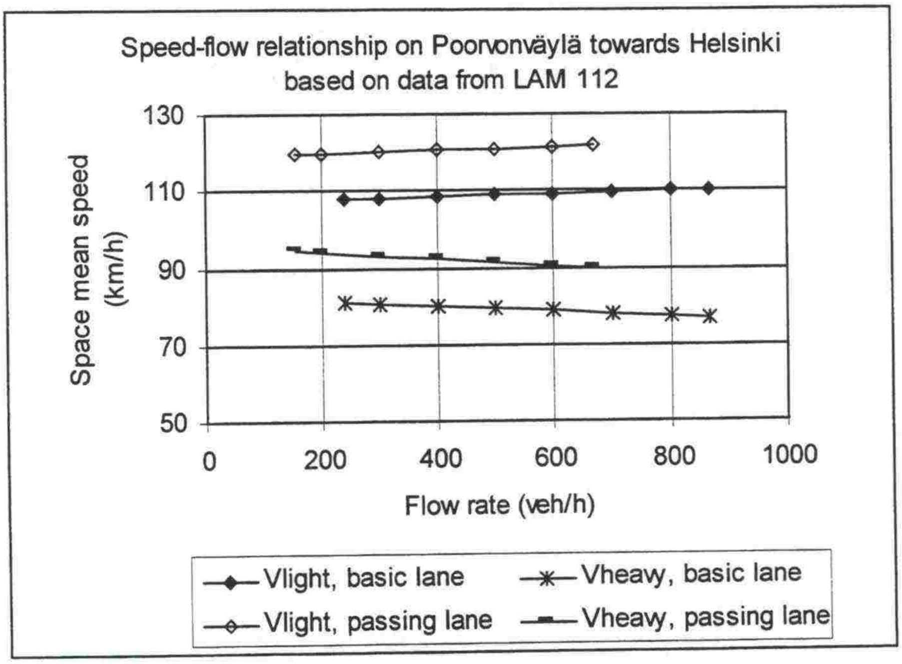

Figure H-9. Speed-flow relationships on Poorvonväylä towards Helsinki.

Appendix I—Space mean speed and average flow rate at different LAM sites

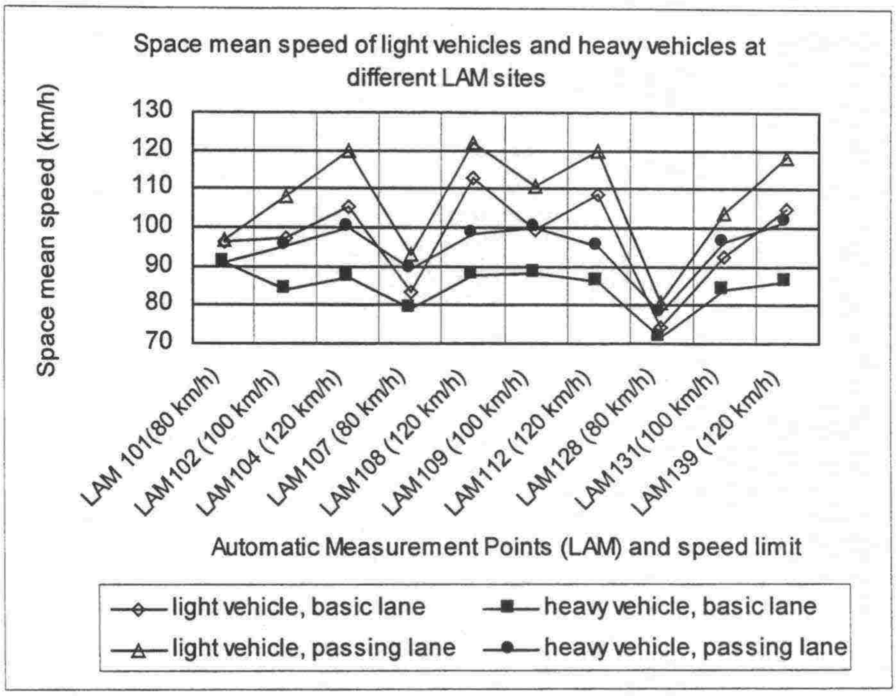

Figure I-1. Space mean speed of light vehicles and heavy vehicles at different LAM sites.

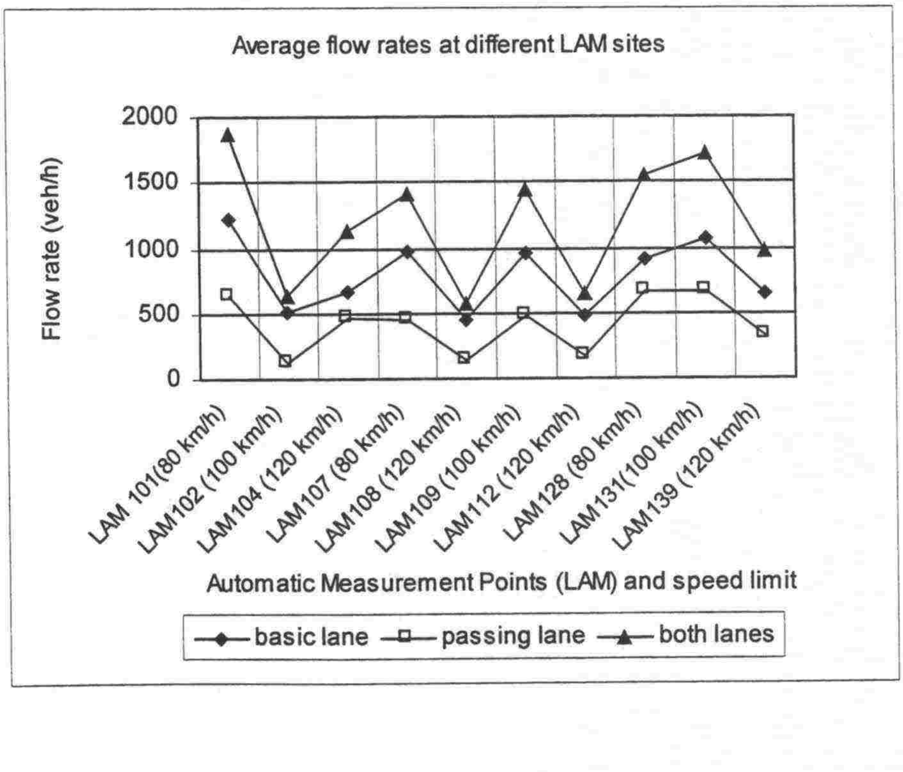

Figure I-2. Average flow rates at different LAM sites.

Appendix J – Cumulative speed distributions based on data from different LAM sites

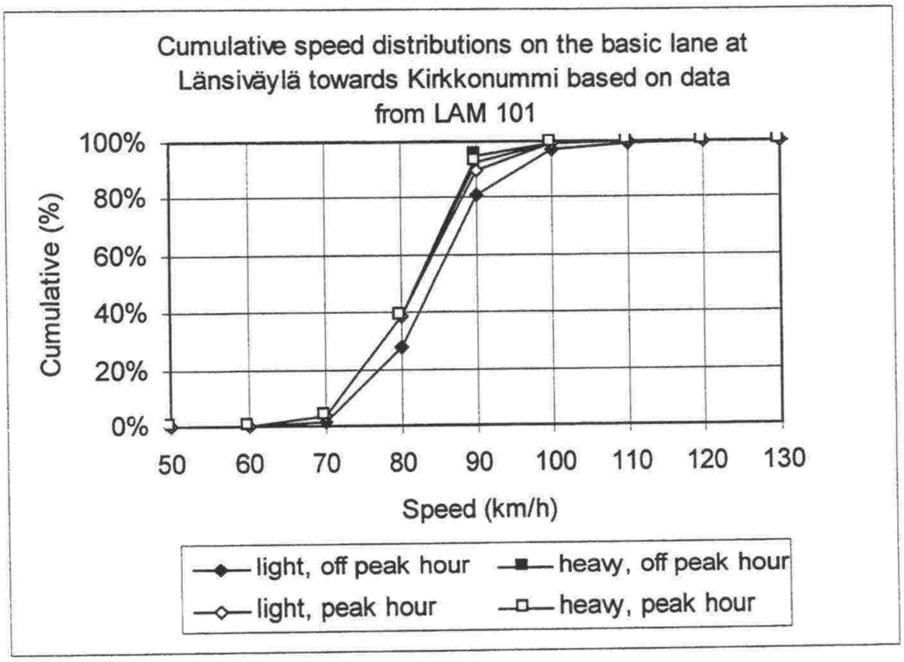

Figure J-1. Cumulative speed distributions on the basic lane at Länsiväylä towards Kirkkonummi based on data from LAM 101 (speed limit 80 km/h).

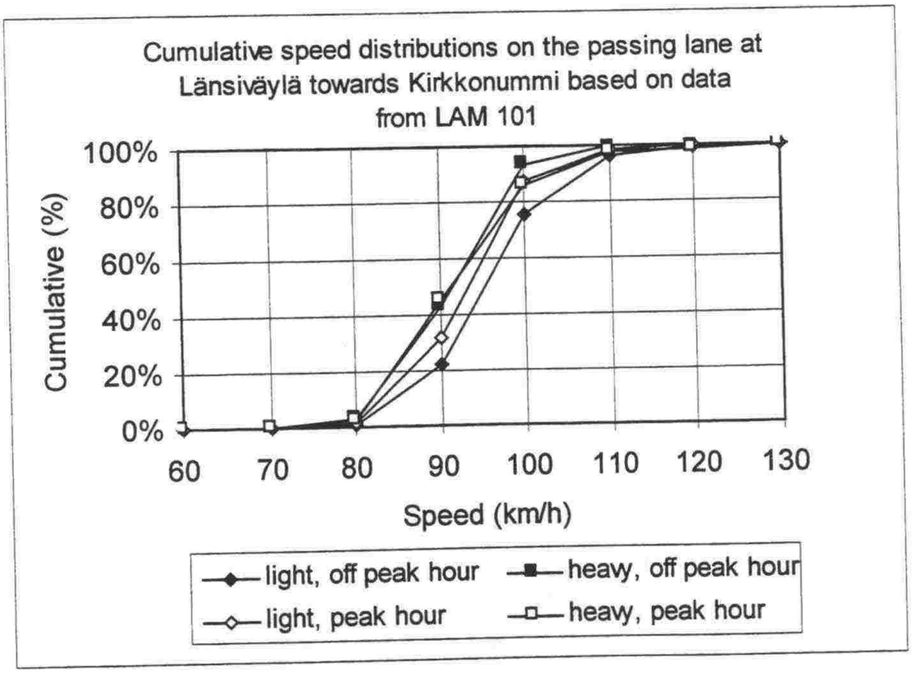

Figure J-2. Cumulative speed distributions on the passing lane at Länsiväylä towards Kirkkonummi based on data from LAM 101 (speed limit 80 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

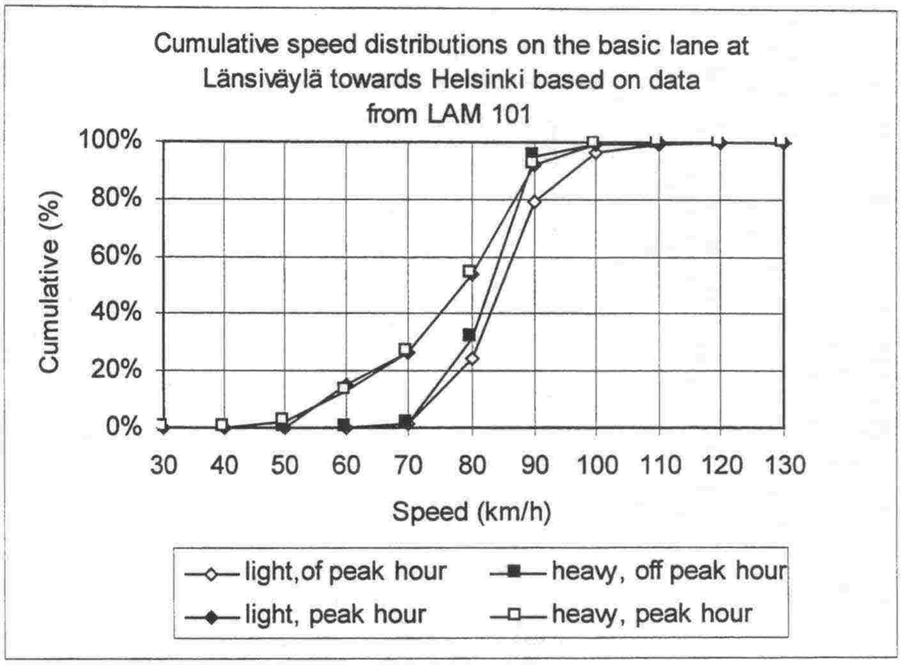

Figure J-3. Cumulative speed distributions on the basic lane at Länsiväylä towards Helsinki based on data from LAM 101 (speed limit 80 km/h).

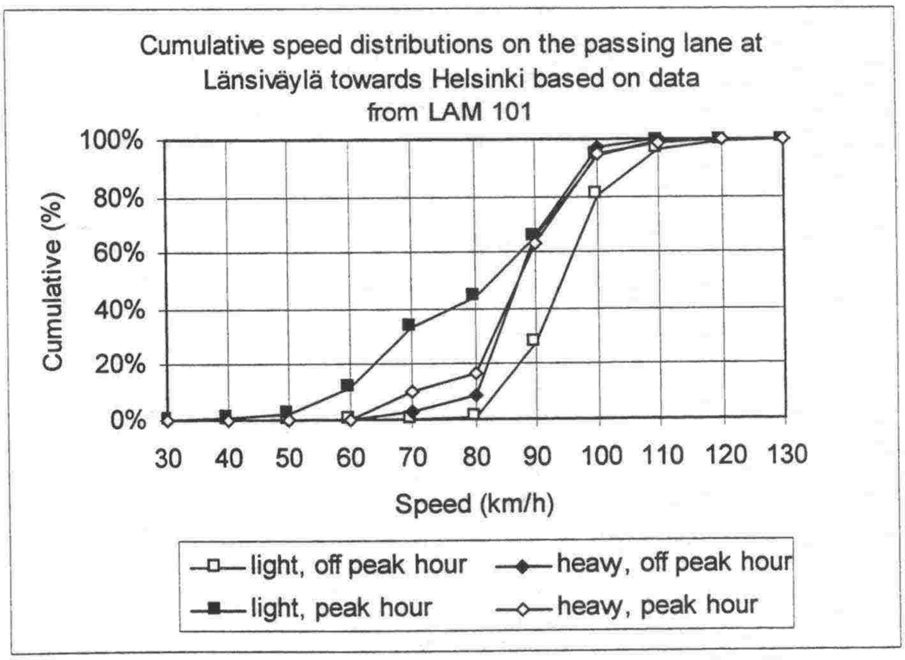

Figure J-4. Cumulative speed distributions on the passing lane at Länsiväylä towards Helsinki based on data from LAM 101 (speed limit 80 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

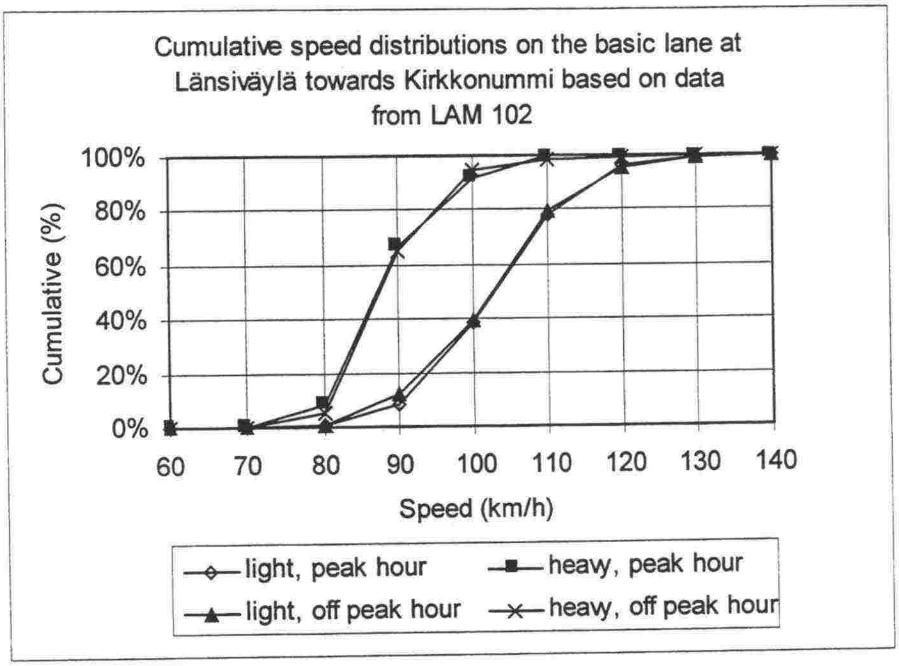

Figure J-5. Cumulative speed distributions on the basic lane at Länsiväylä towards Kirkkonummi based on data from LAM 102 (speed limit 100 km/h).

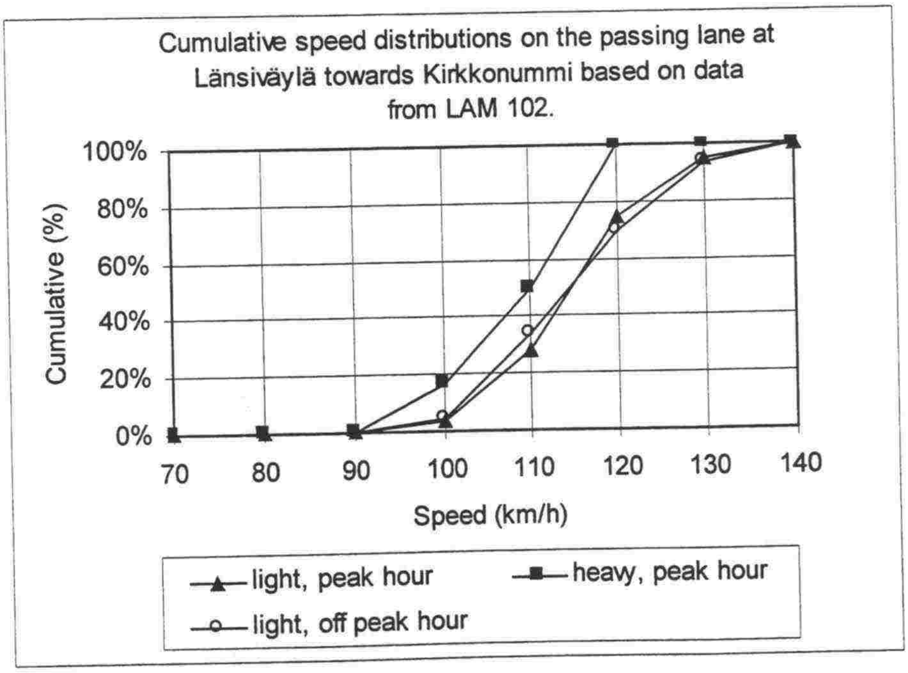

Figure J-6. Cumulative speed distributions on the passing lane at Länsiväylä towards Kirkkonummi based on data from LAM 102 (speed limit 100 km/h)

Appendix J – Cumulative speed distributions based on data from different LAM sites

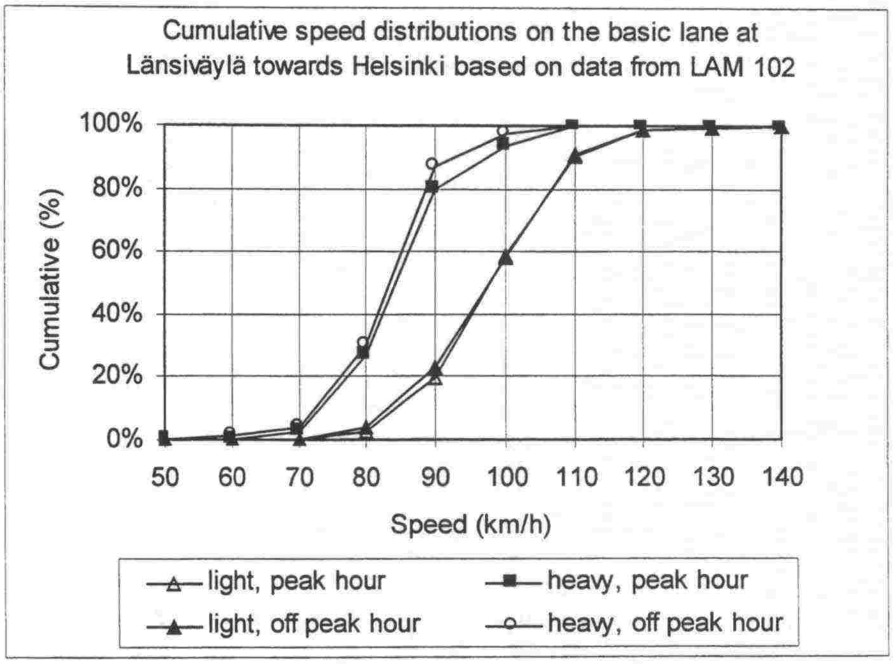

Figure J-7. Cumulative speed distributions at Länsiväylä towards Helsinki based on data from LAM 102 (speed limit 100 km/h).

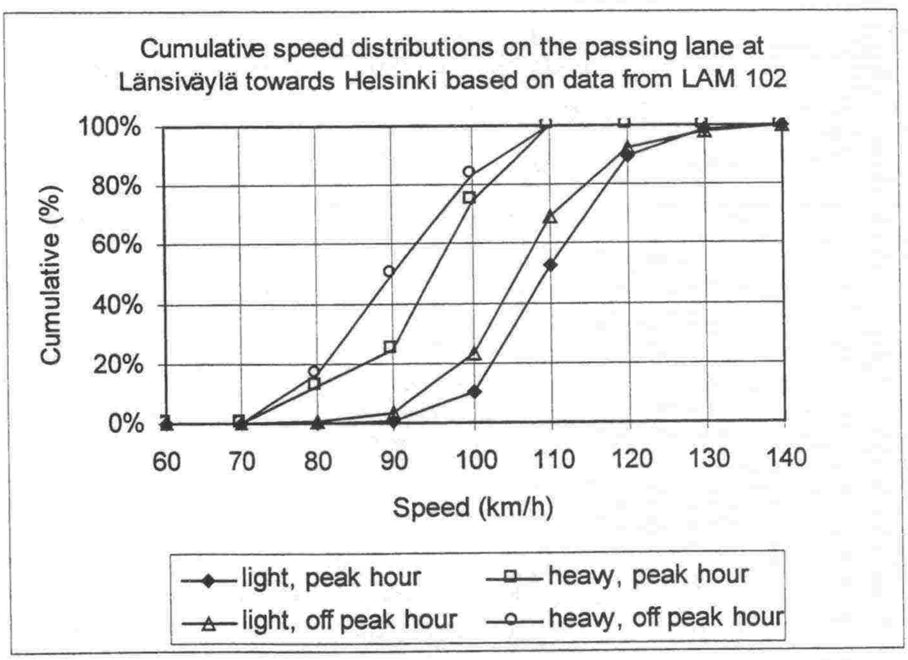

Figure J-8. Cumulative speed distributions on the passing lane at Länsiväylä towards Helsinki based on data from LAM 102 (speed limit 100 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

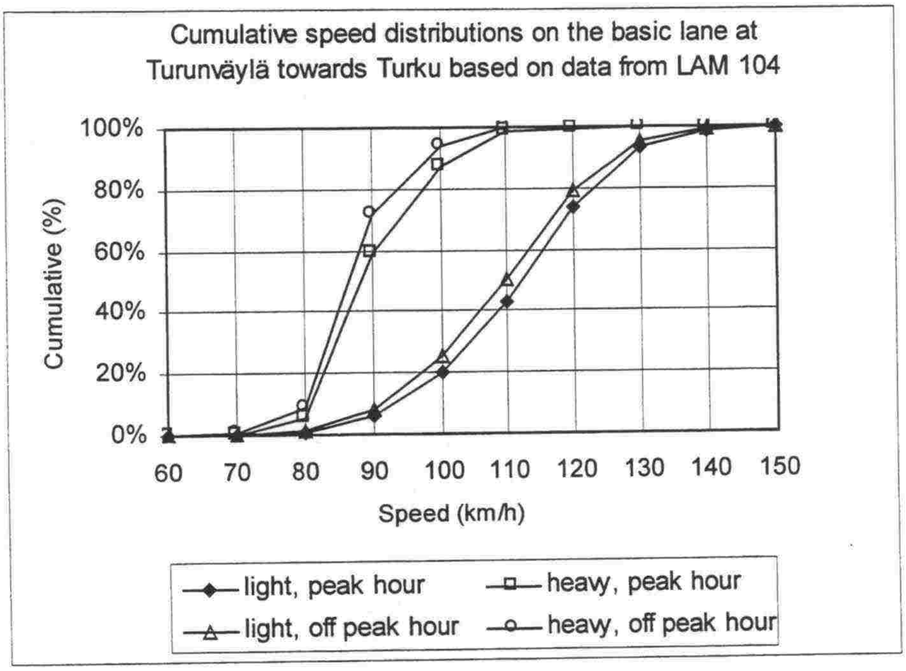

Figure J-9. Cumulative speed distributions on the basic lane at Turunväylä towards Turku based on data from LAM 104 (speed limit 120 km/h).

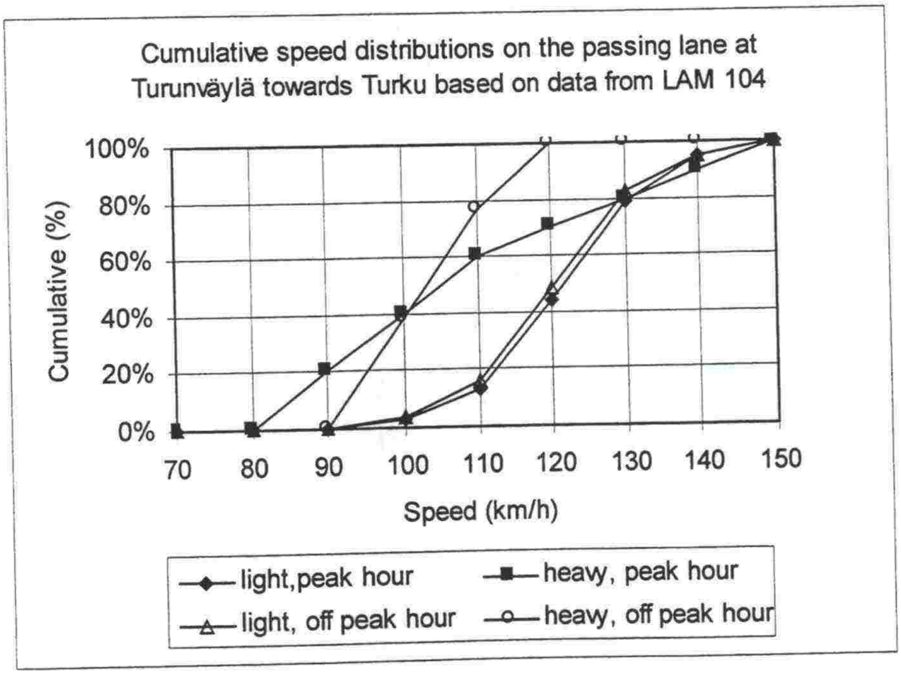

Figure J-10. Cumulative speed distributions on the passing lane at Turunväylä towards Turku based on data from LAM 104 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

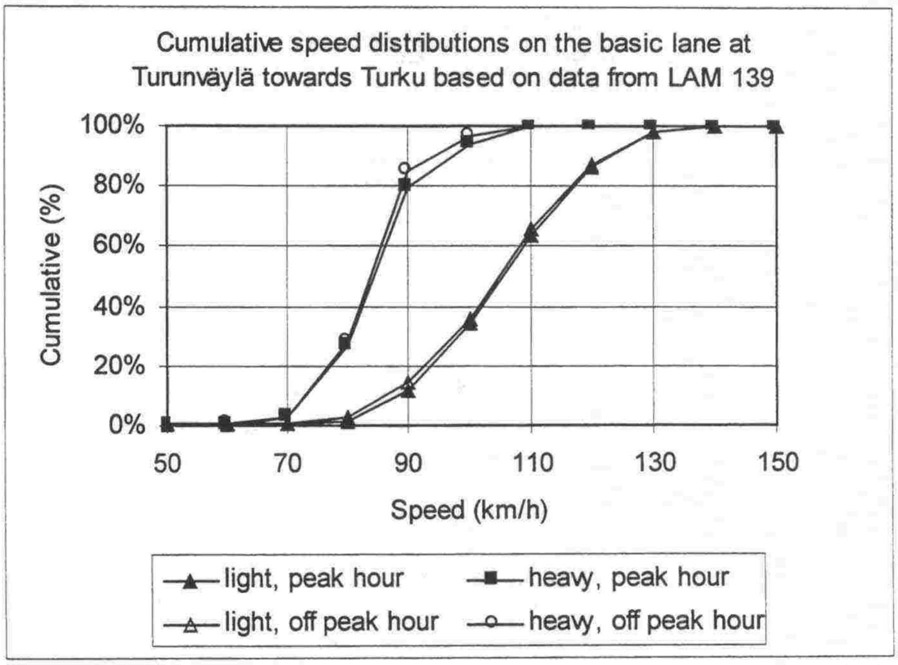

Figure J-11. Cumulative speed distributions on the basic lane at Turunväylä towards Turku based on data from LAM 139 (speed limit 120 km/h).

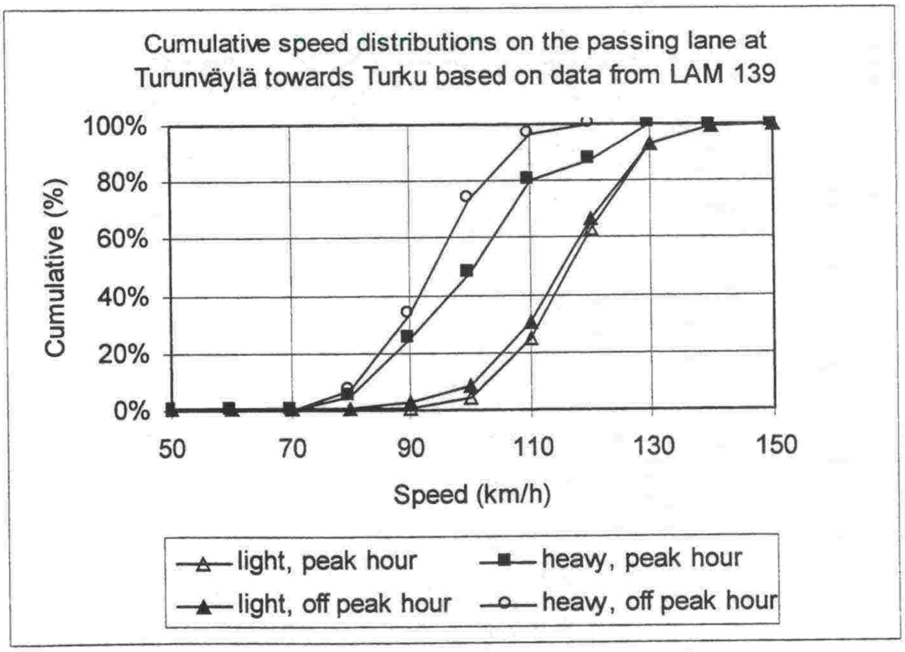

Figure J-12. Cumulative speed distributions on the passing lane at Turunväylä towards Turku based on data from LAM 139 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

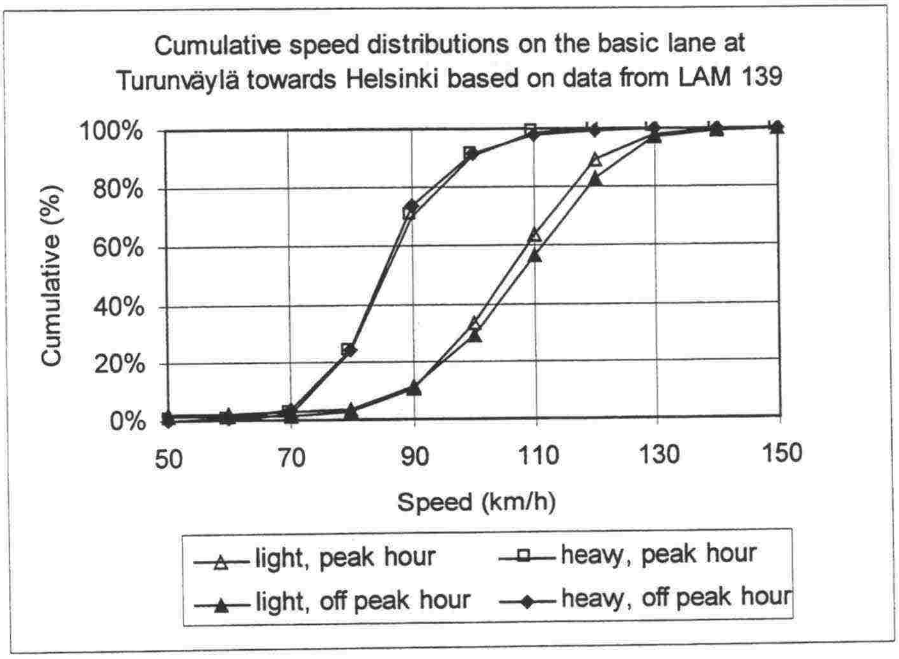

Figure J-13. Cumulative speed distributions on the basic lane at Turunväylä towards Helsinki based on data from LAM 139 (speed limit 120 km/h).

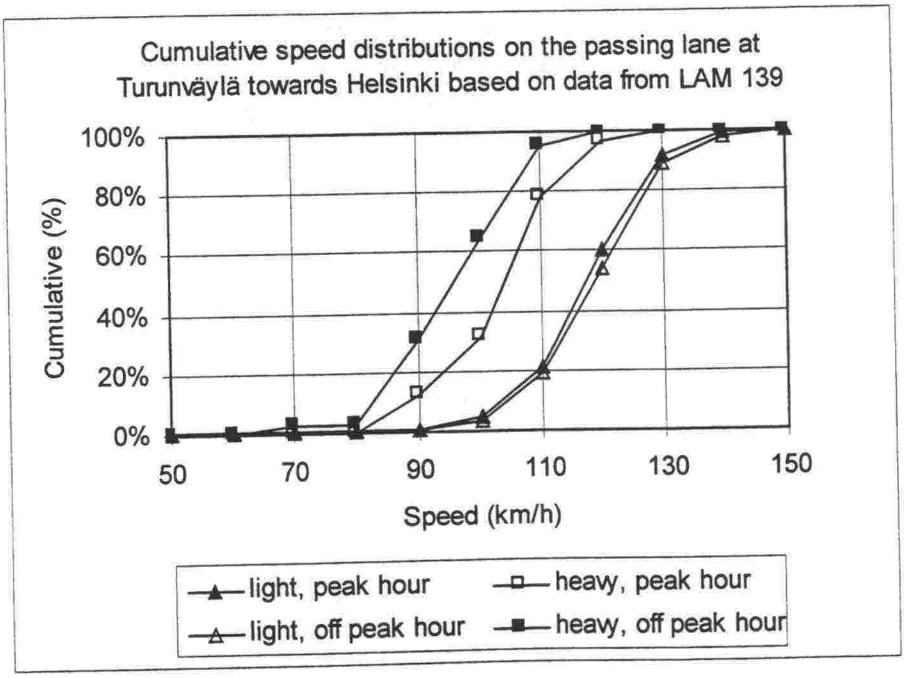

Figure J-14. Cumulative speed distributions on the passing lane at Turunväylä towards Helsinki based on data from LAM 139 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

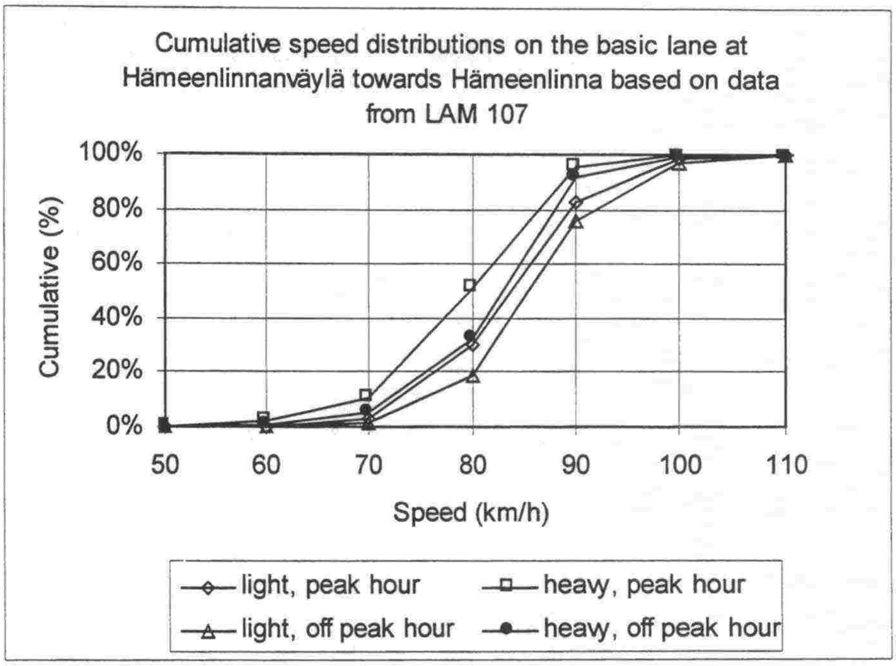

Figure J-15. Cumulative speed distributions on the basic lane at Hämeenlinnanväylä towards Hämeenlinna based on data from LAM 107 (speed limit 80 km/h).

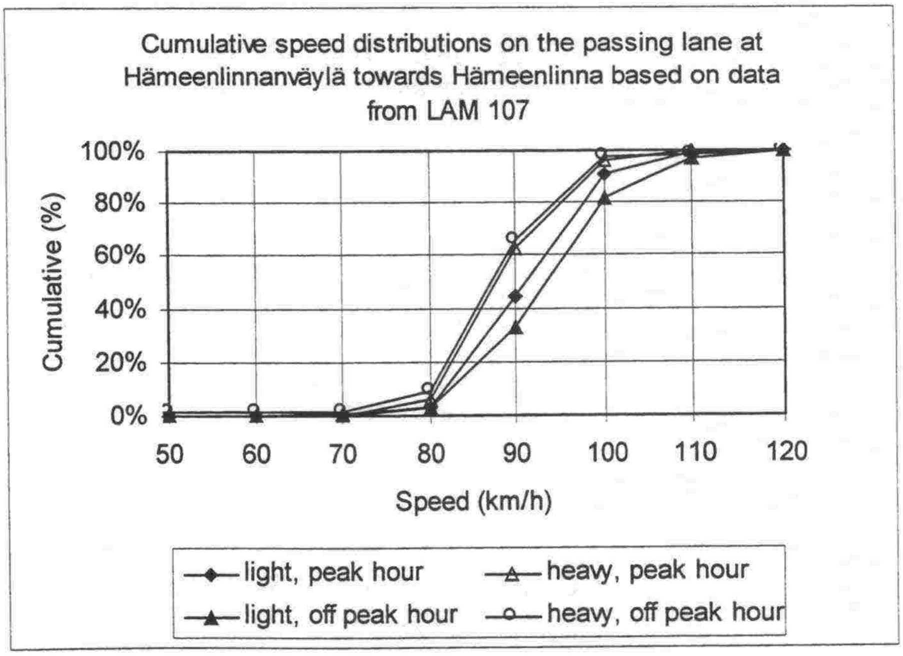

Figure J-16. Cumulative speed distributions on the passing lane at Hämeenlinnanväylä towards Hämeenlinna based on data from LAM 107 (speed limit 80 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

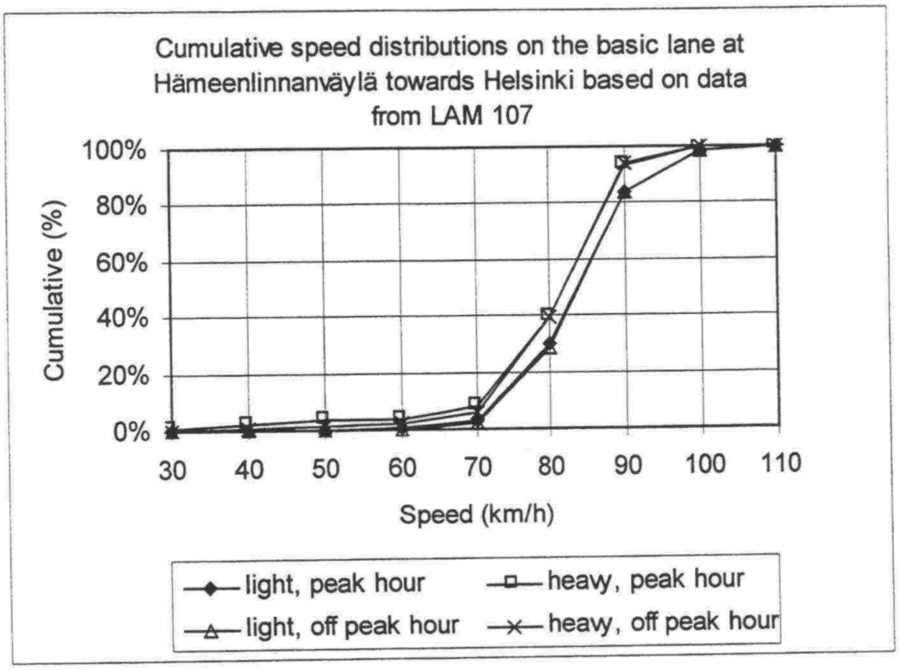

Figure J-17. Cumulative speed distributions on the basic lane at Hämeenlinnanväylä towards Helsinki based on data from LAM 107 (speed limit 80 km/h).

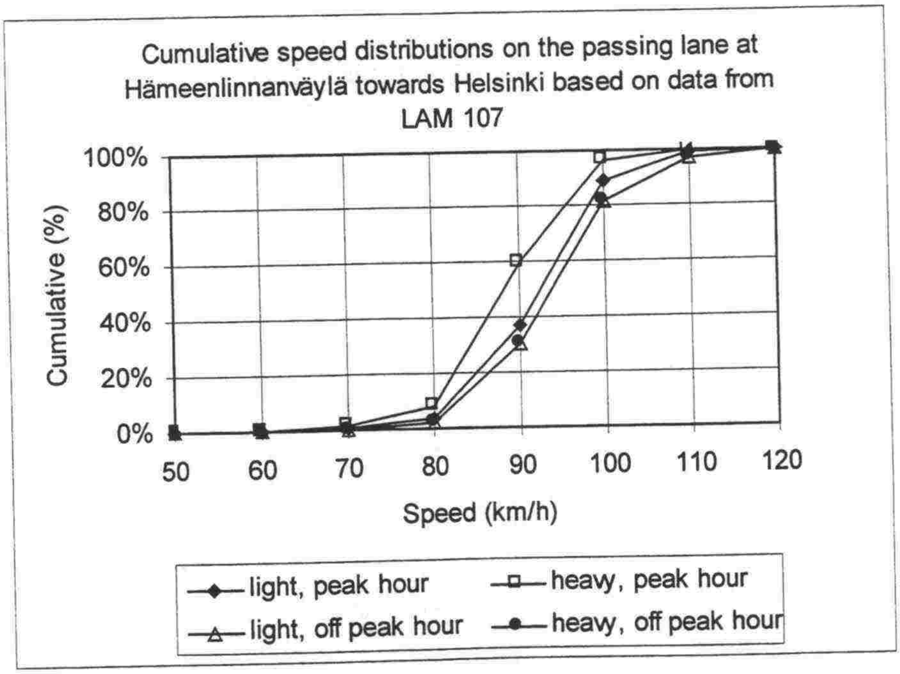

Figure J-18. Cumulative speed distributions on the passing lane at Hämeenlinnanväylä towards Helsinki based on data from LAM 107 (speed limit 80 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

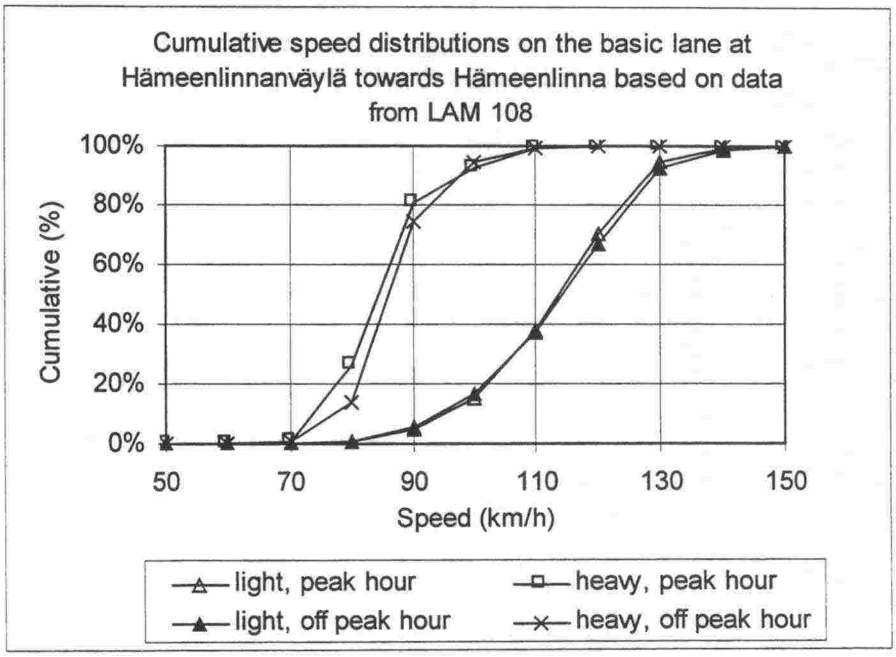

Figure J-19. Cumulative speed distributions on the basic lane at Hämeenlinnanväylä towards Hämeenlinna based on data from LAM 108 (speed limit 120 km/h).

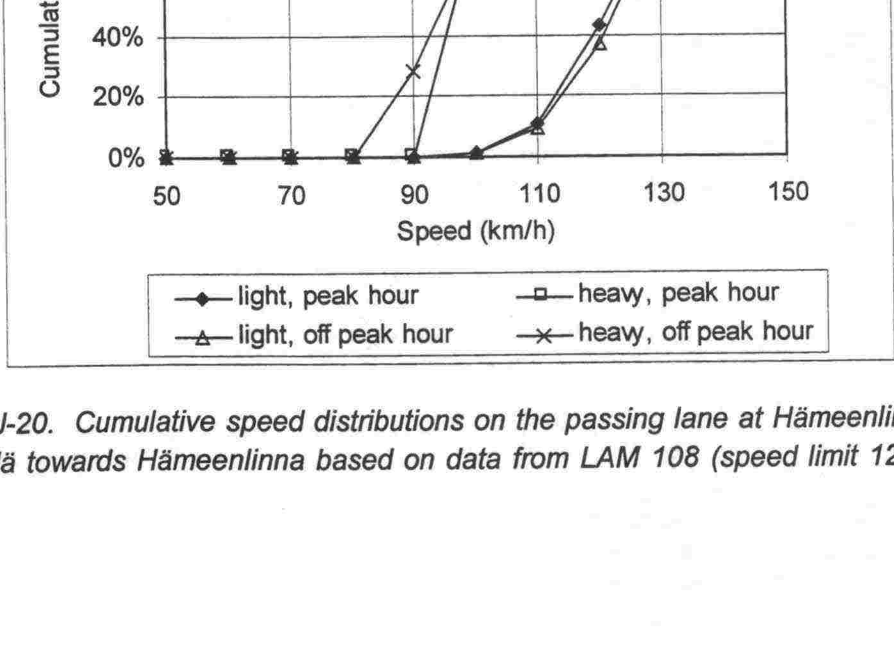

Figure J-20. Cumulative speed distributions on the passing lane at Hämeenlinnanväylä towards Hämeenlinna based on data from LAM 108 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

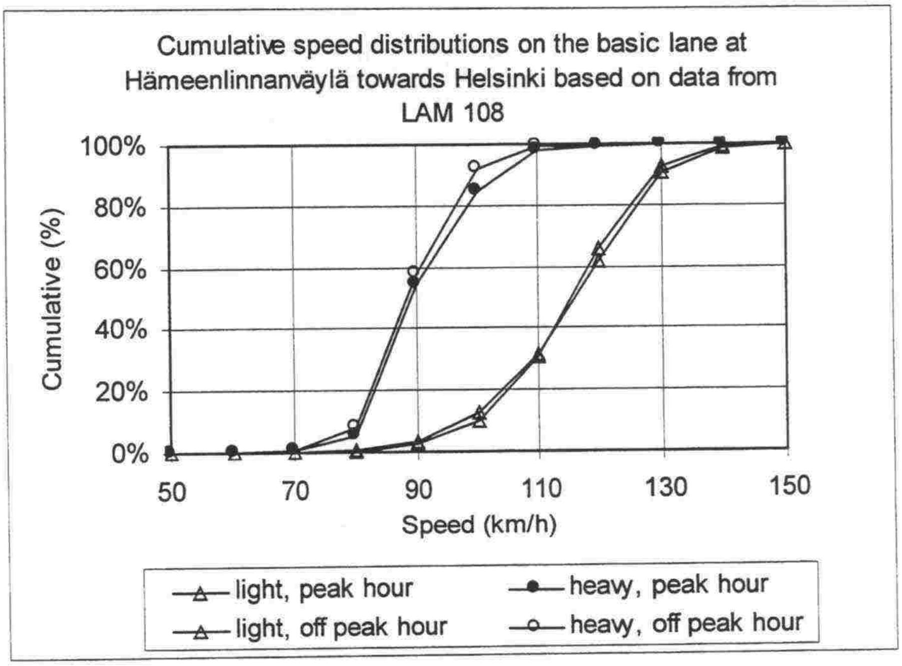

Figure J-21. Cumulative speed distributions on the basic lane at Hämeenlinnanväylä towards Helsinki based on data from LAM 108 (speed limit 120 km/h).

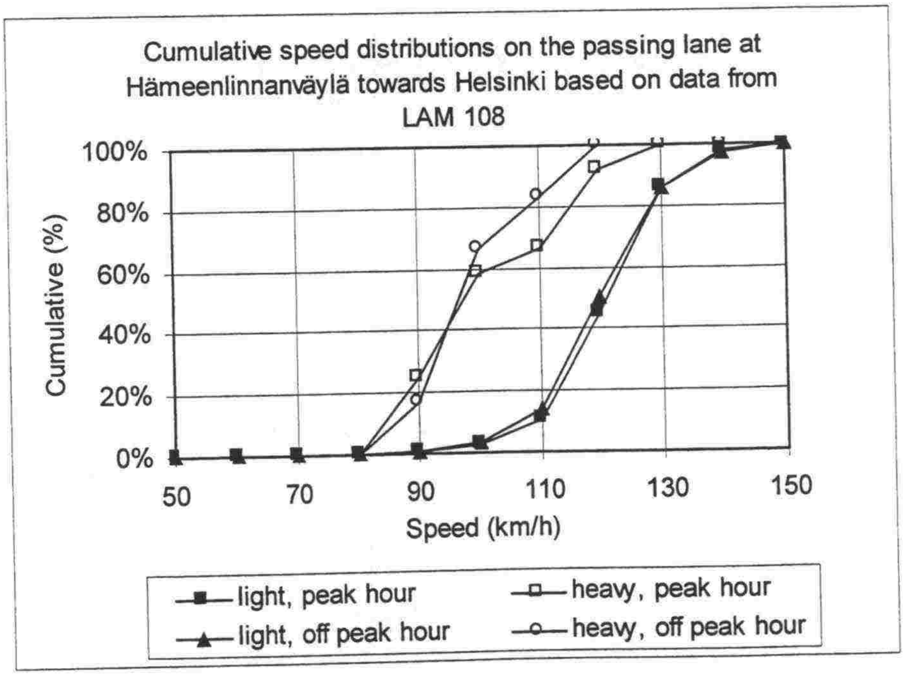

Figure J-22. Cumulative speed distributions on the passing lane at Hämeenlinnanväylä towards Helsinki based on data from LAM 108 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

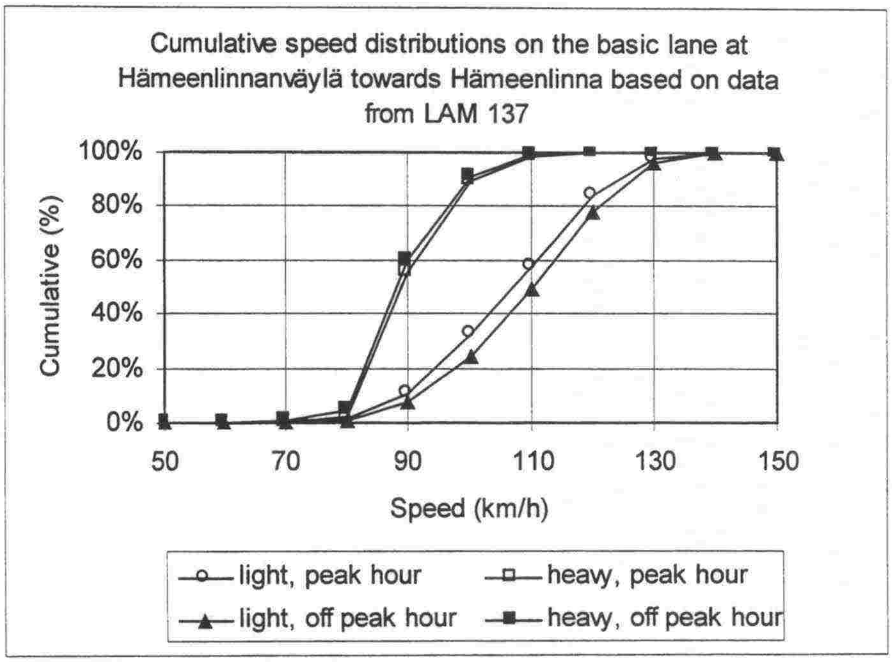

Figure J-23. Cumulative speed distributions on the basic lane at Hämeenlinnanväylä towards Hämeenlinna based on data from LAM 139 (speed limit 120 km/h).

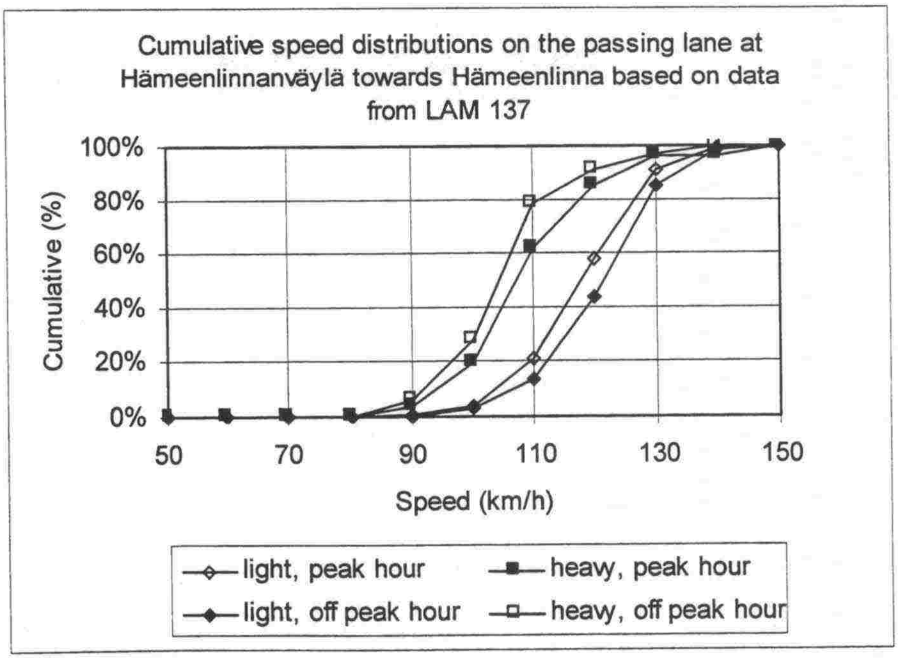

Figure J-24. Cumulative speed distributions on the passing lane at Hämeenlinnanväylä towards Hameenlinna based on data from LAM 137 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

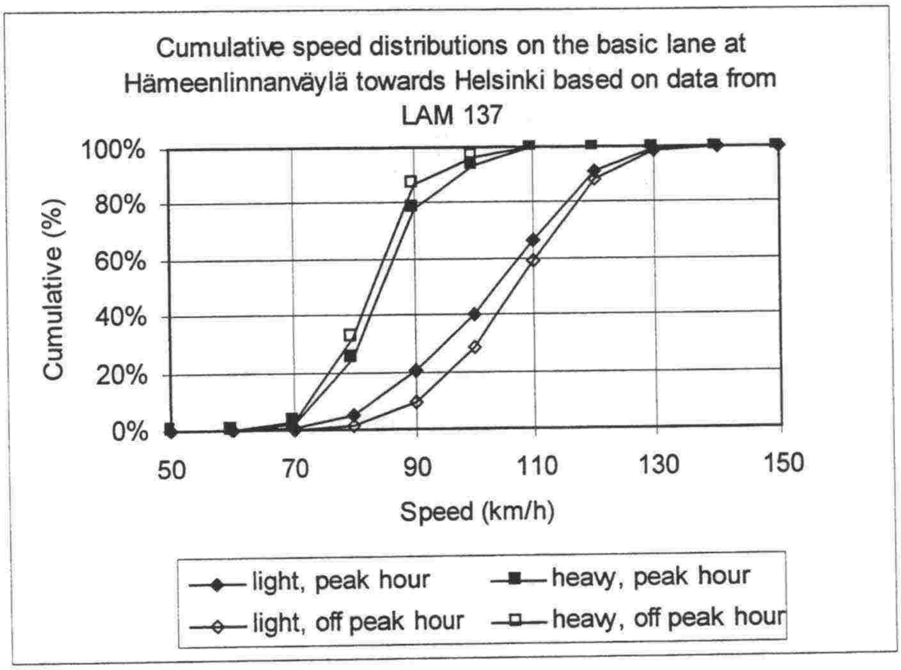

Figure J-25. Cumulative speed distributions on the basic lane at Hämeenlinnanväylä towards Helsinki based on data from LAM 137 (speed limit 120 km/h).

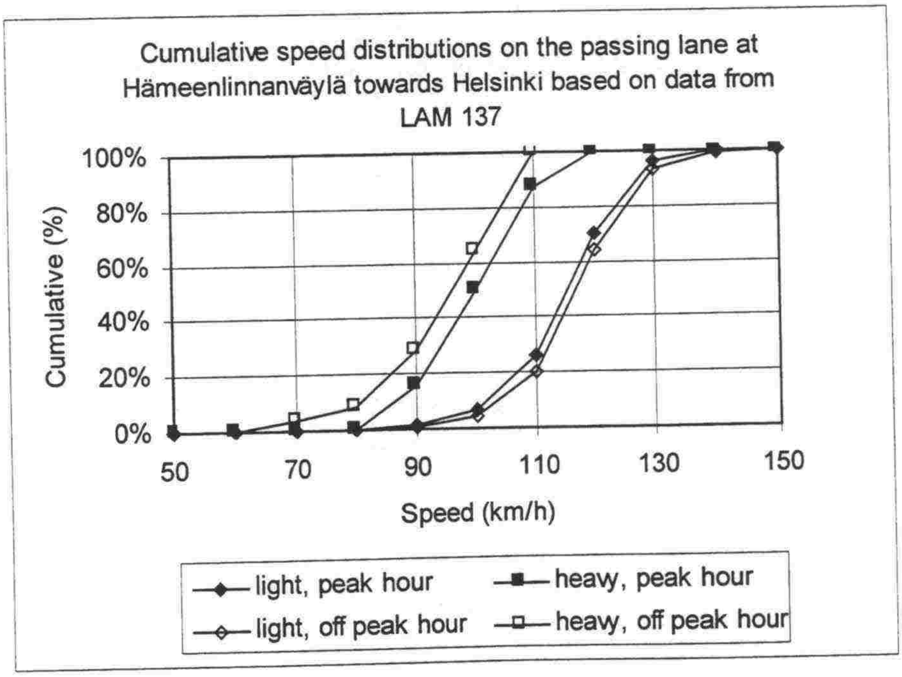

Figure J-26. Cumulative speed distributions on the passing lane at Hämeenlinnanväylä towards Helsinki based on data from LAM 137 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

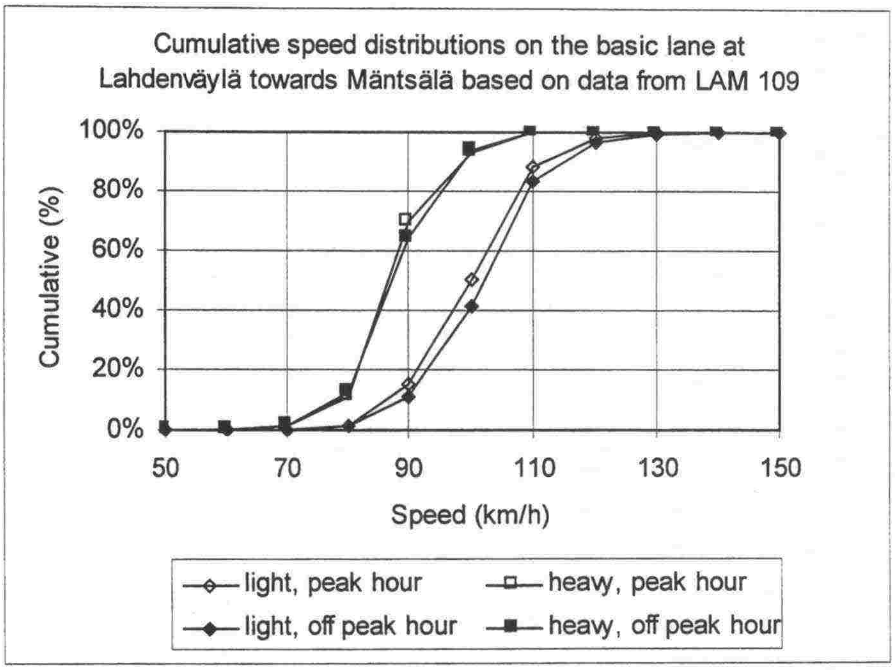

Figure J-27. Cumulative speed distributions on the basic lane at Lahdenväylä towards Mäntsälä based on data from LAM 109 (speed limit 100 km/h).

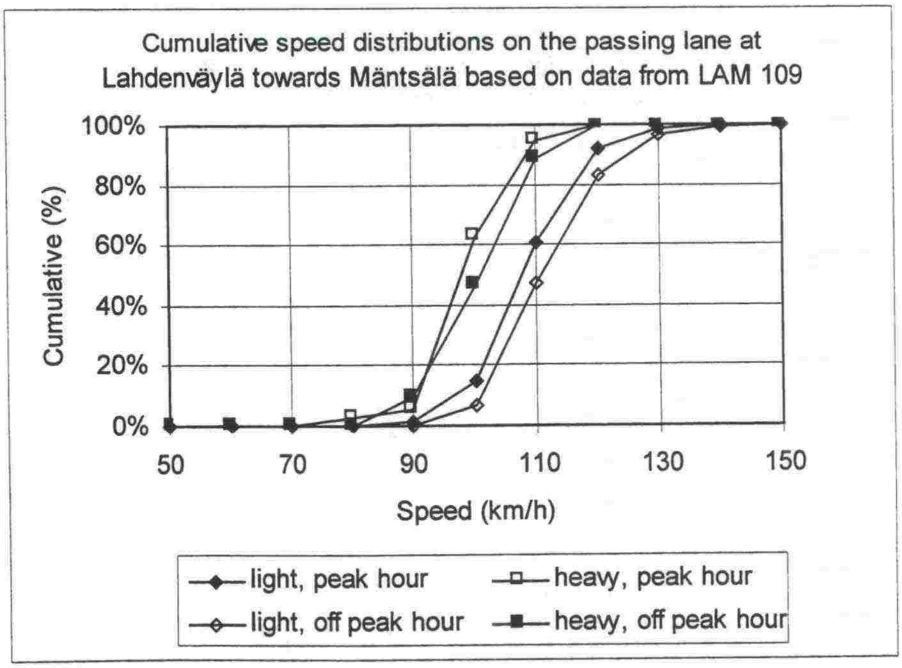

Figure J-28. Cumulative speed distributions on the passing lane at Lahdenväylä towards Mäntsälä based on data from LAM 109 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

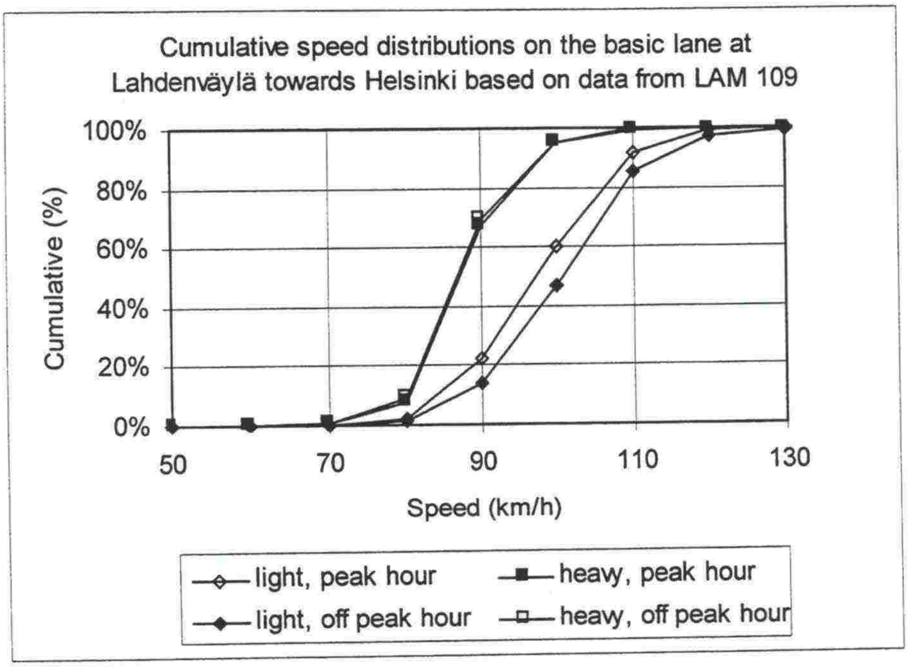

Figure J-29. Cumulative speed distributions on the basic lane at Lahdenväylä towards Helsinki based on data from LAM 109 (speed limit 100 km/h).

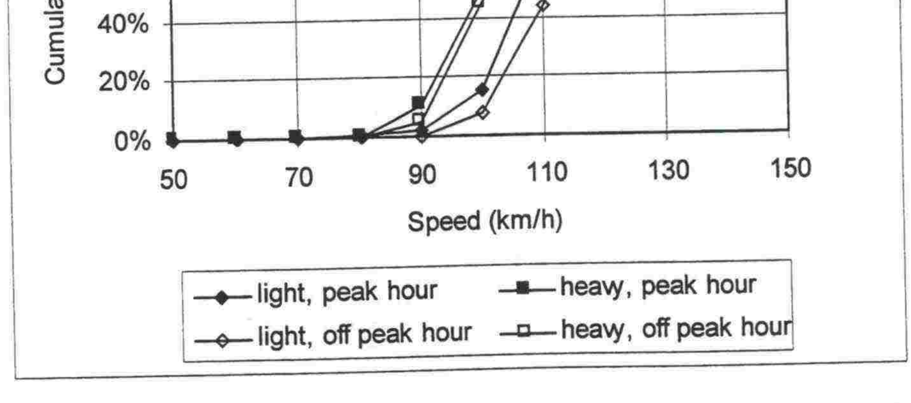

Figure J-30. Cumulative speed distributions on the passing lane at Lahdenväylä towards Helsinki based on data from LAM 109 (speed limit 100 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

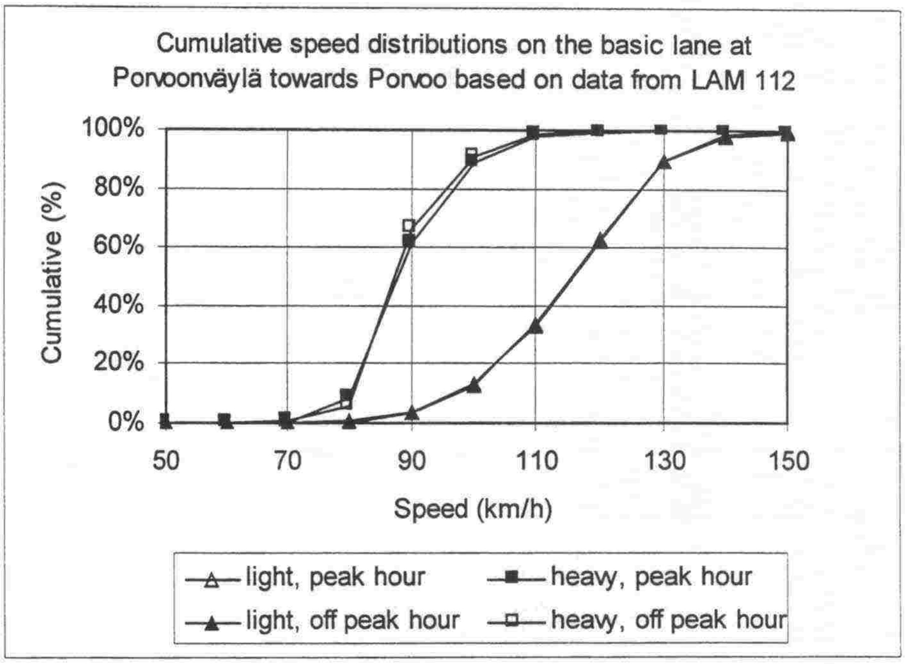

Figure J-31. Cumulative speed distributions on the basic lane at Porvoonväylä towards Porvoo based on data from LAM 112 (speed limit 120 km/h).

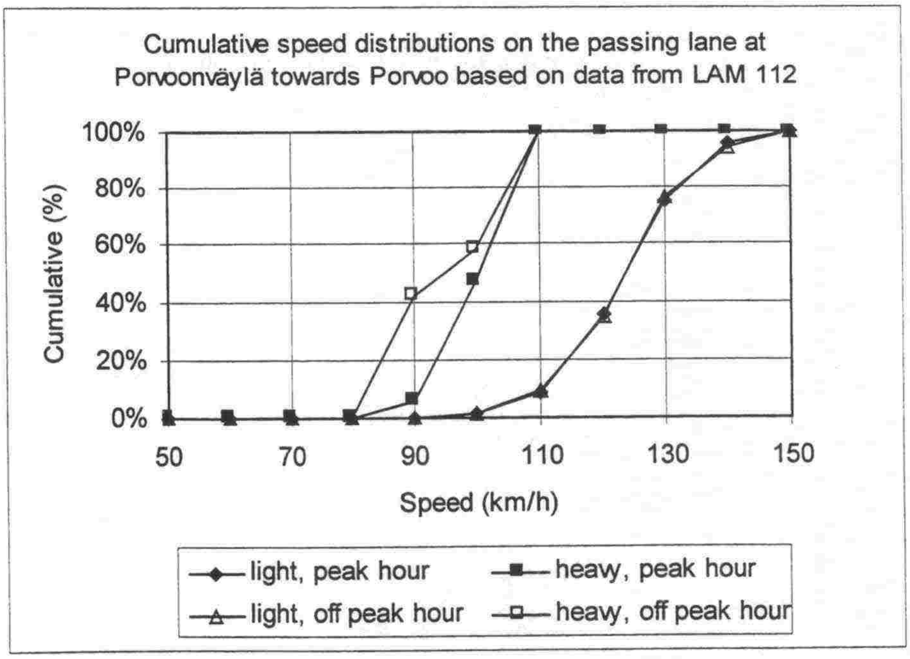

Figure J-32. Cumulative speed distributions on the passing lane at Porvoonväylä towards Porvoo based on data from LAM 112 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

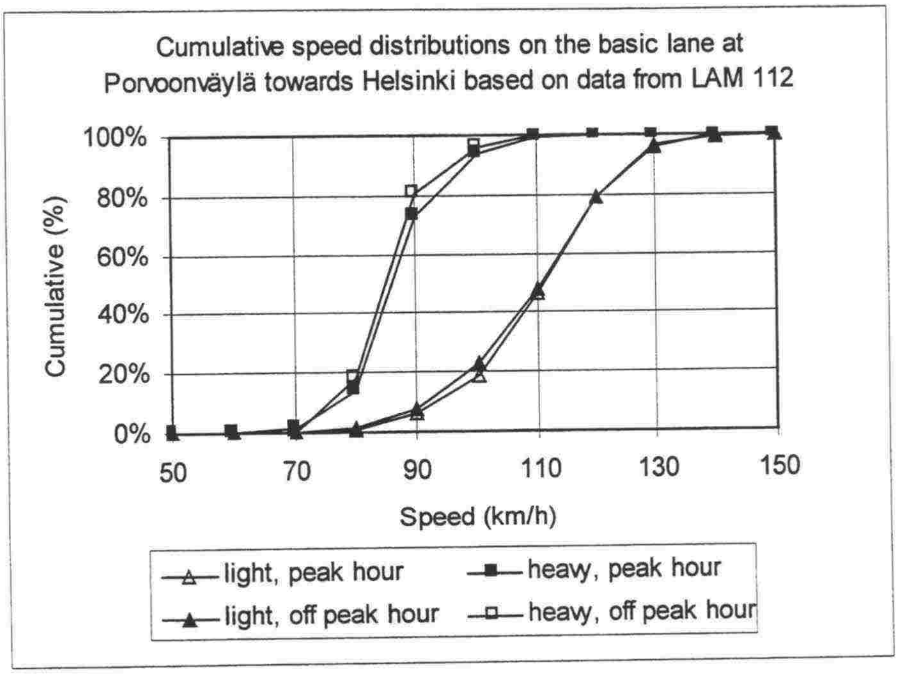

Figure J-33. Cumulative speed distributions on the basic lane at Porvoonväylä towards Helsinki based on data from LAM 112 (speed limit 120 km/h).

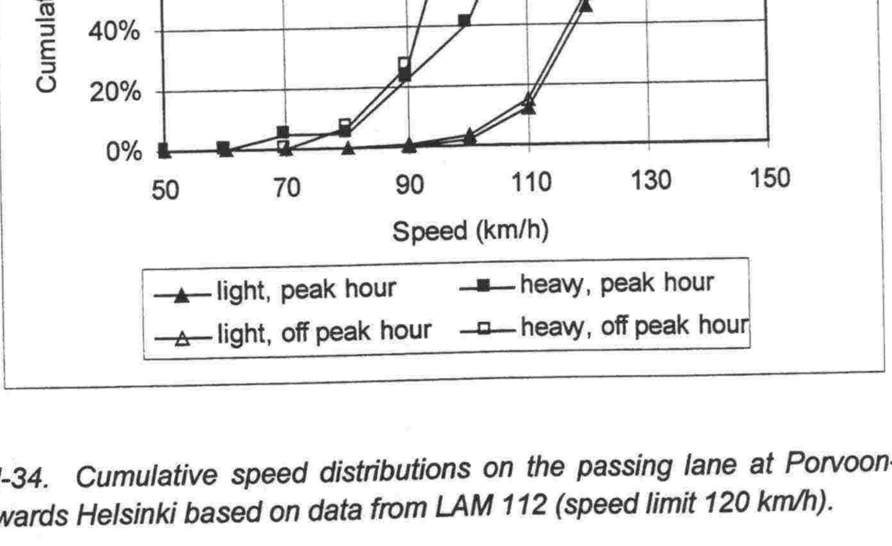

Figure J-34. Cumulative speed distributions on the passing lane at Porvoonväylä towards Helsinki based on data from LAM 112 (speed limit 120 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

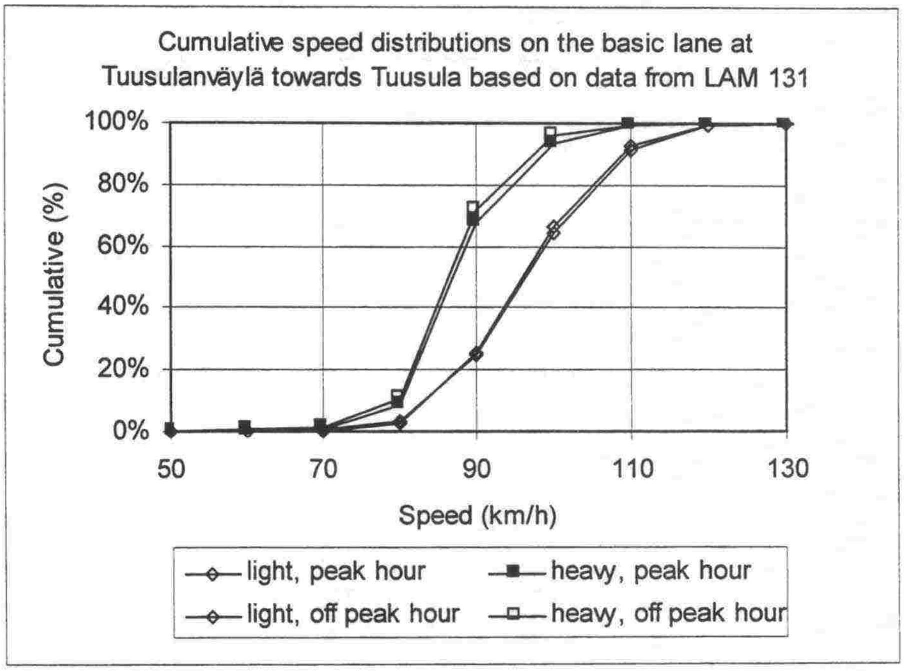

Figure J-35. Cumulative speed distributions on the basic lane at Tuusulanväylä towards Tuusula based on data from LAM 131 (speed limit 100 km/h).

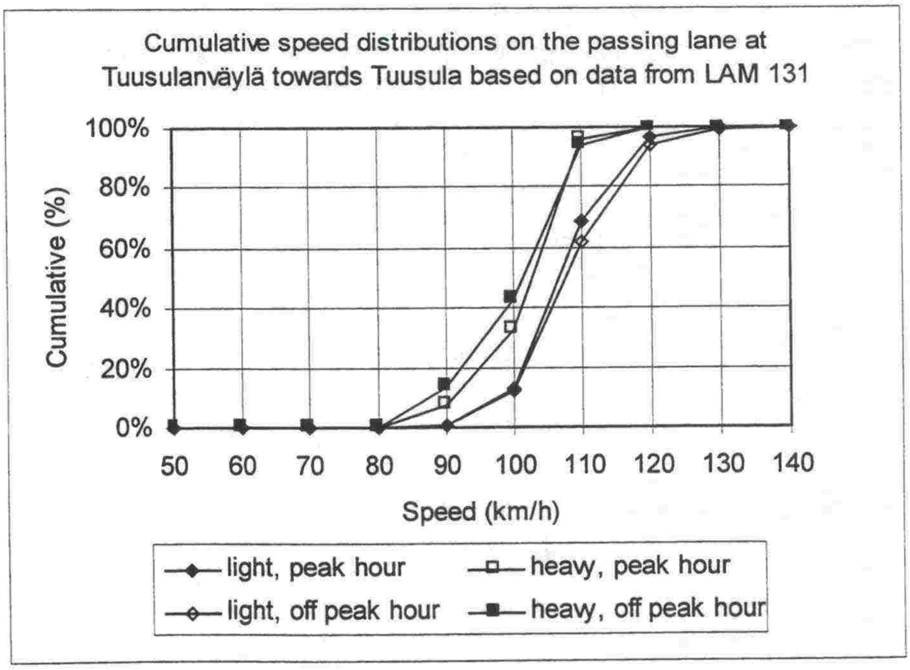

Figure J-36. Cumulative speed distributions on the passing lane at Tuusulanväylä towards Tuusula based on data from LAM 131 (speed limit 100 km/h).

Appendix J – Cumulative speed distributions based on data from different LAM sites

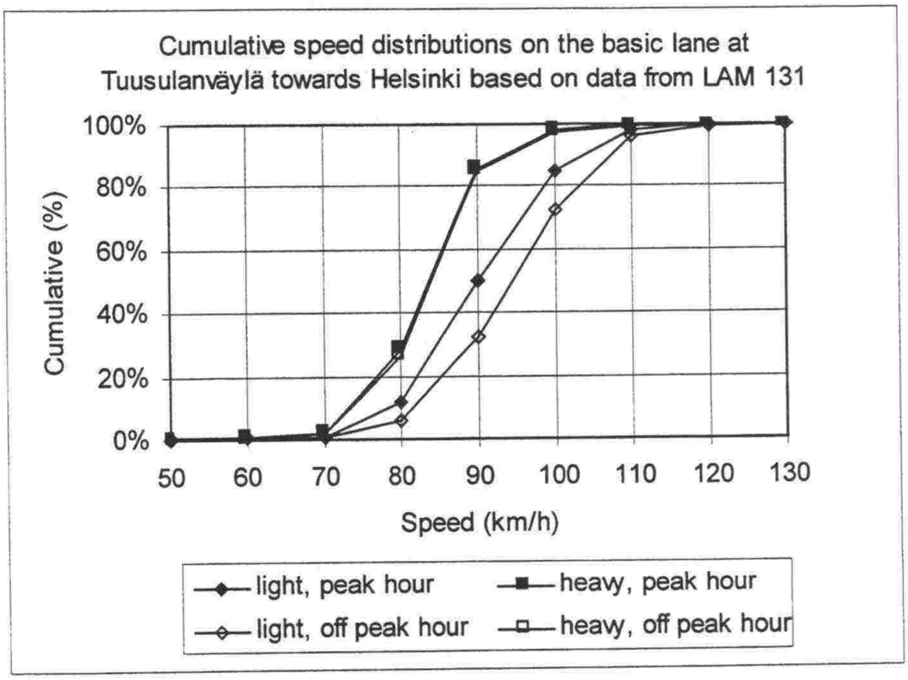

Figure J-37. Cumulative speed distributions on the basic lane at Tuusulanväylä towards Helsinki based on data from LAM 131 (speed limit 100 km/h).

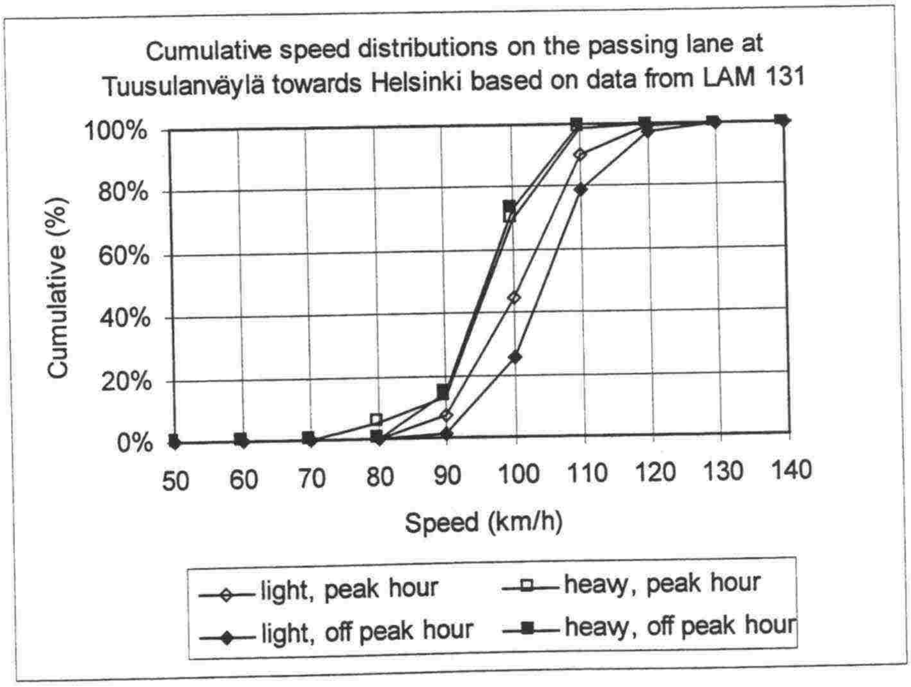

Figure J-38. Cumulative speed distributions on the passing lane at Tuusulanväylä towards Helsinki based on data from LAM 131 (speed limit 100 km/h).

Appendix K—Space mean speed and flow rate at different LAM sites, both lanes together

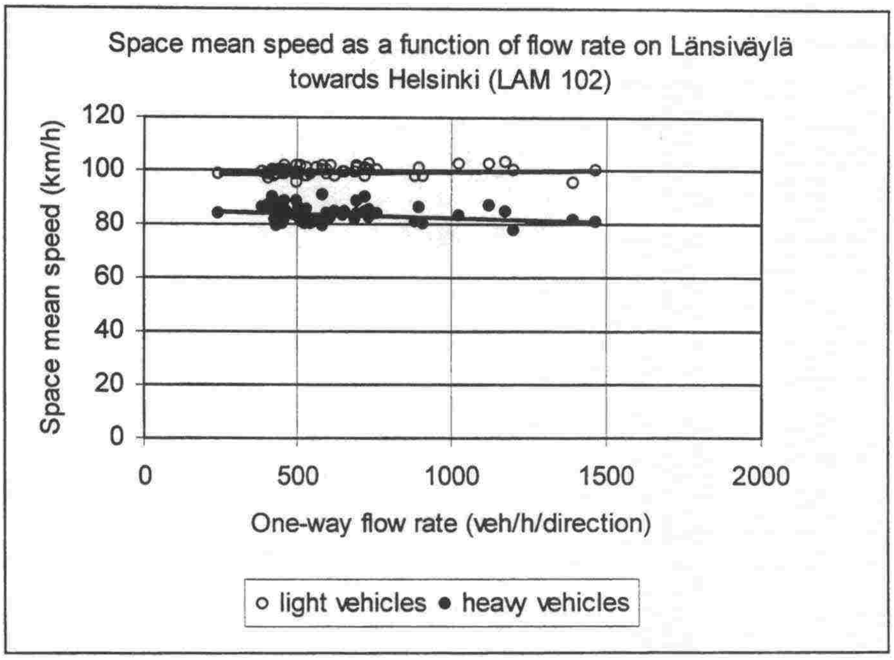

Figure K-1. Space mean speed for light vehicles and heavy vehicles on Länsiväylä towards Helsinki (speed limit 100 km/h).

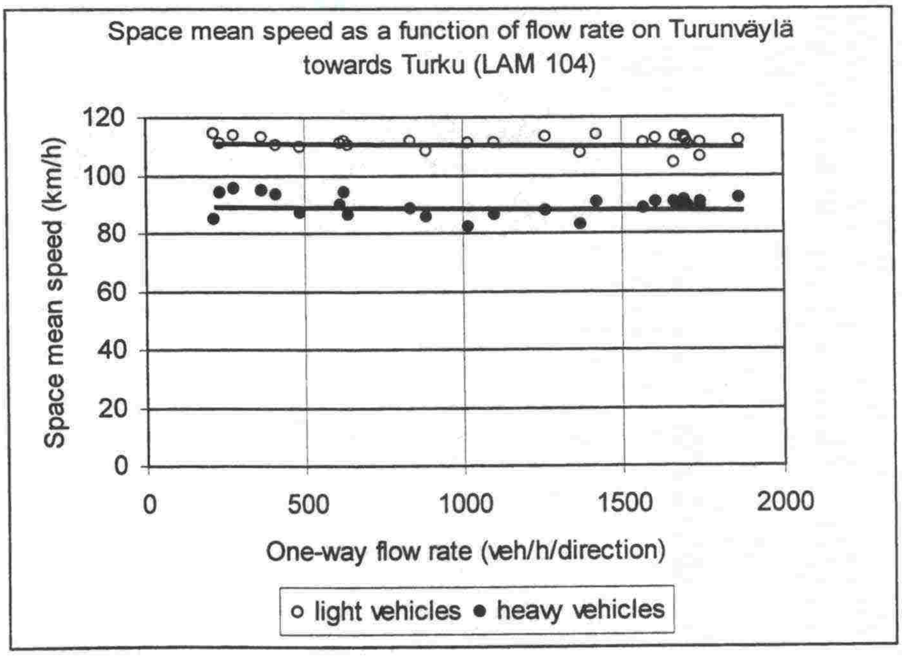

Figure K-2. Space mean speed for light vehicles and heavy vehicles on Turunväylä towards Turku (speed limit 120 km/h).

Appendix K—Space mean speed and flow rate at different LAM sites, both lanes together

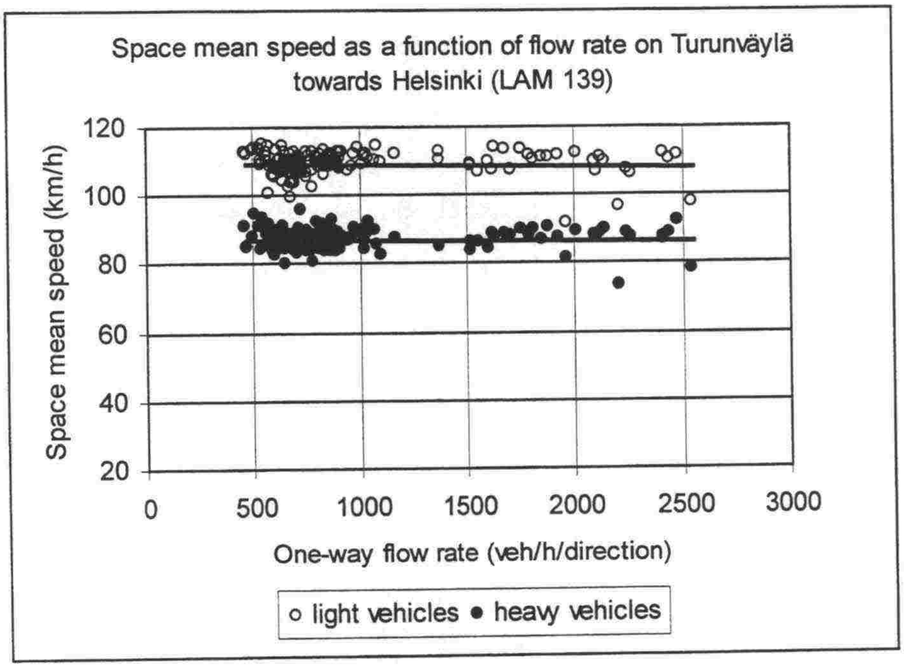

Figure K-3. Space mean speed for light vehicles and heavy vehicles on Turunväylä towards Helsinki (speed limit 120 km/h).

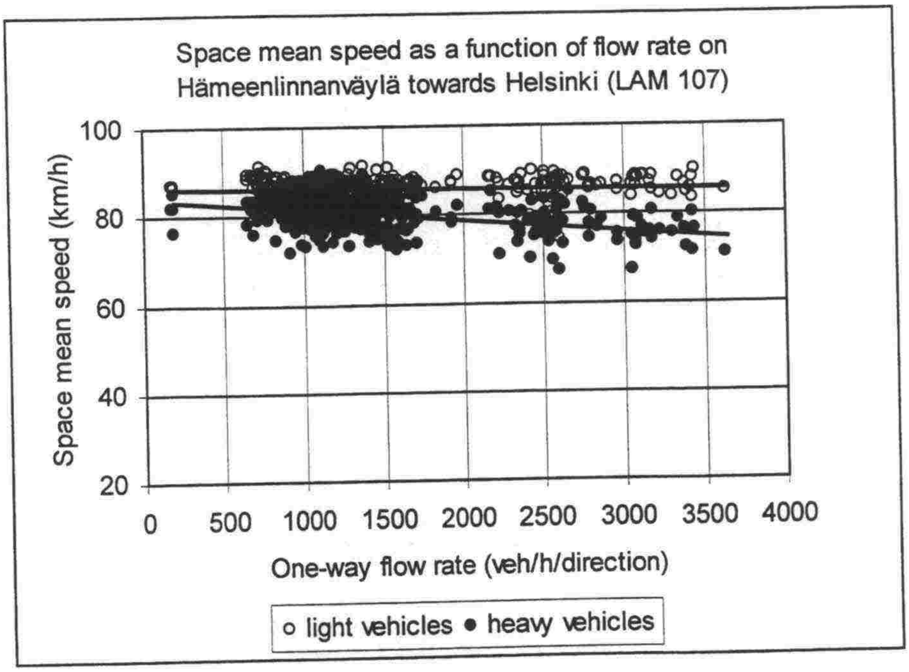

Figure K-4. Space mean speed for light vehicles and heavy vehicles on Hämeenlinnanväylä towards Helsinki (speed limit 80 km/h).

Appendix K—Space mean speed and flow rate at different LAM sites, both lanes together

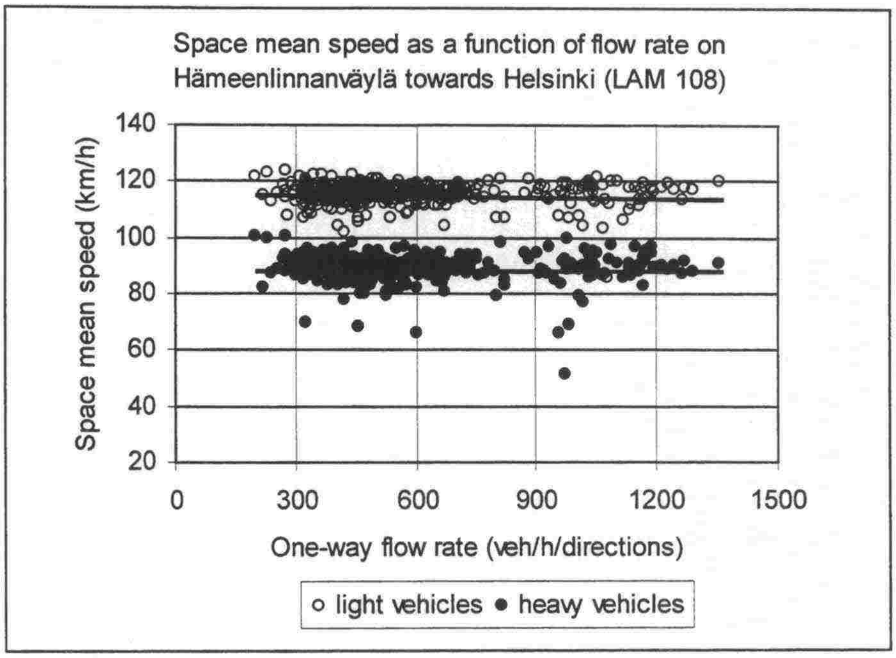

Figure K-5. Space mean speed for light vehicles and heavy vehicles on Hämeenlinnanväylä towards Helsinki (speed limit 120 km/h).

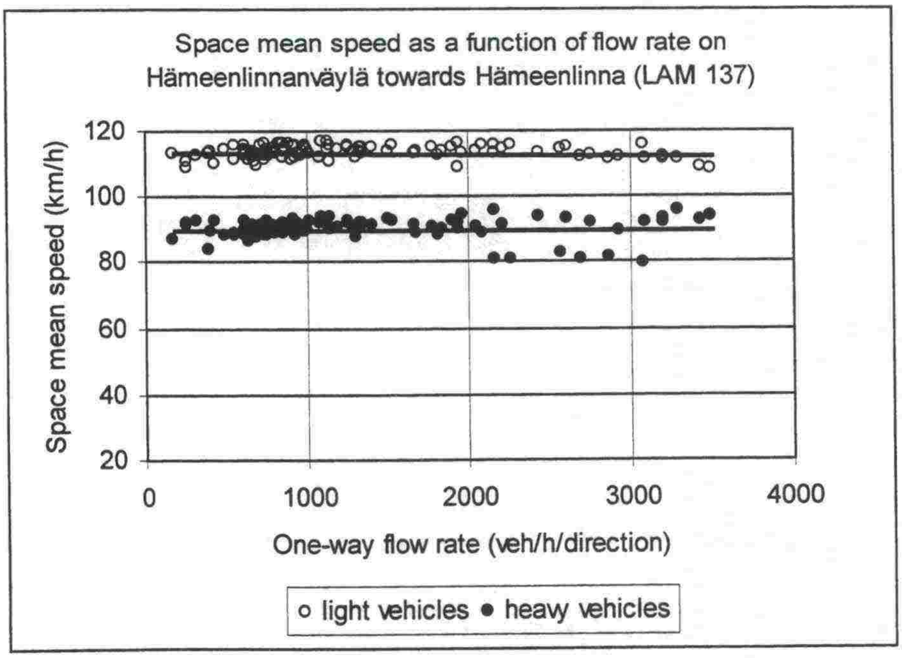

Figure K-6. Space mean speed for light vehicles and heavy vehicles on Hämeenlinnanväylä towards Hämeenlinna (speed limit 120 km/h).

Appendix K—Space mean speed and flow rate at different LAM sites, both lanes together

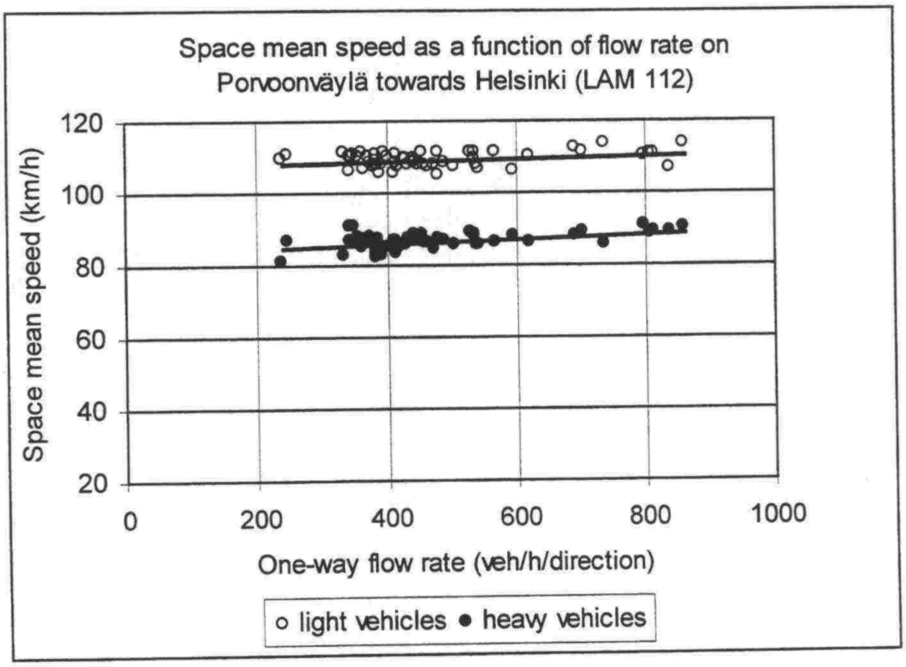

Figure K-7. Space mean speed for light vehicles and heavy vehicles on Porvoonväylä towards Porvoo (speed limit 120 km/h).

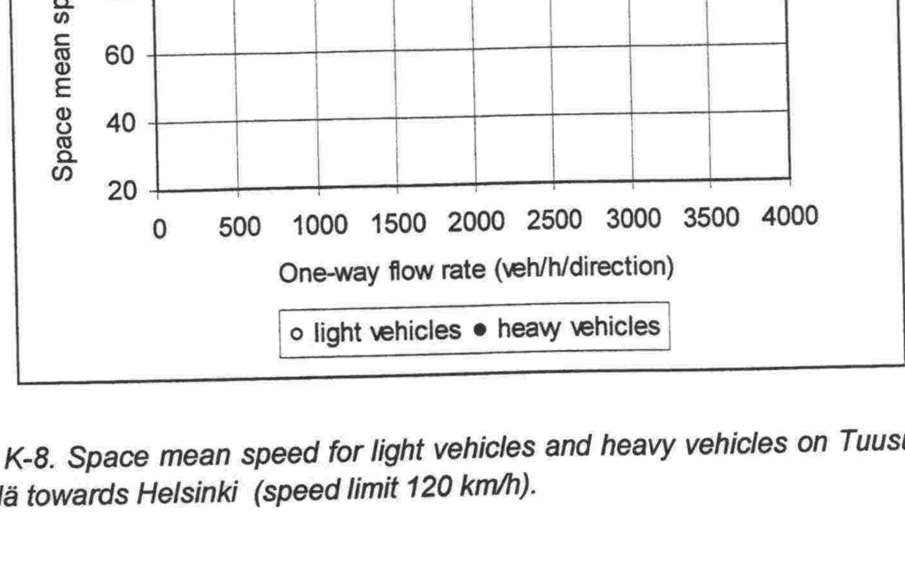

Figure K-8. Space mean speed for light vehicles and heavy vehicles on Tuusulanväylä towards Helsinki (speed limit 120 km/h).

Appendix L—Space mean speed and flow rate on basic lane and passing lane at different speed limit areas

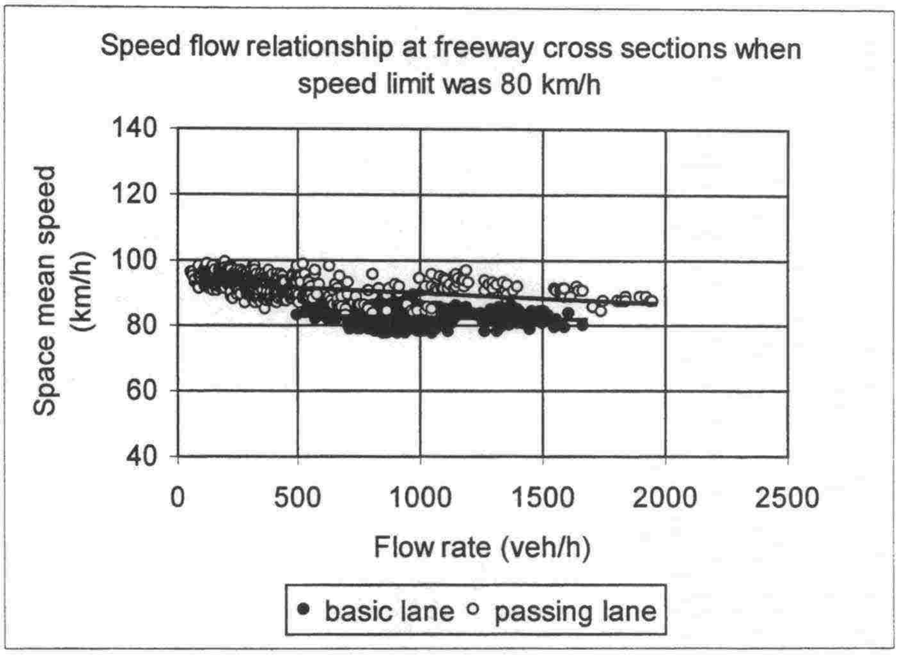

Figure L-1. Speed flow relationship at freeway cross sections when speed limit was 80 km/h.

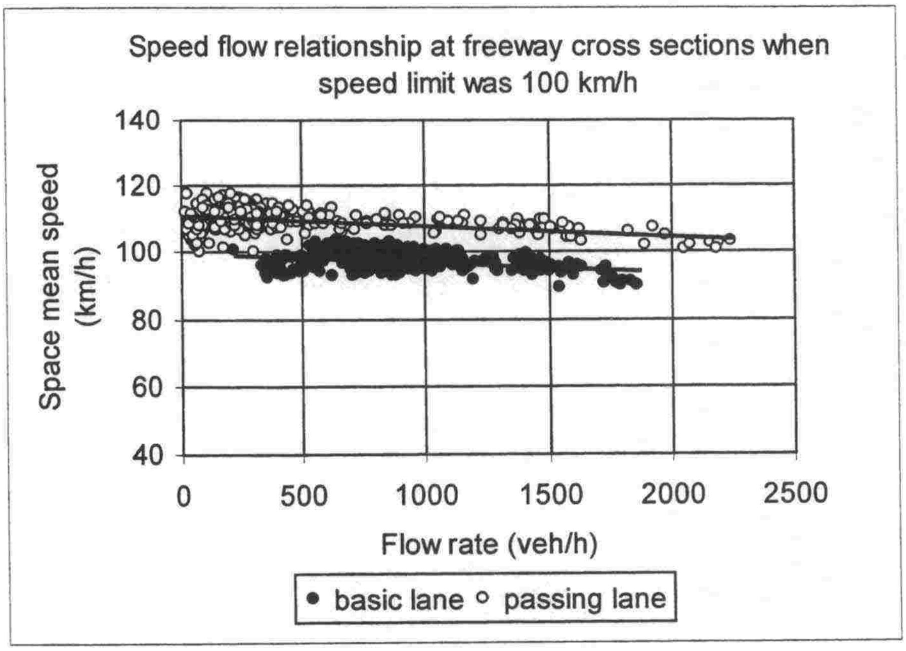

Figure L-2. Speed flow relationship at freeway cross sections when speed limit was 100 km/h.

Appendix L—Space mean speed and flow rate on basic lane and passing lane at different speed limit areas

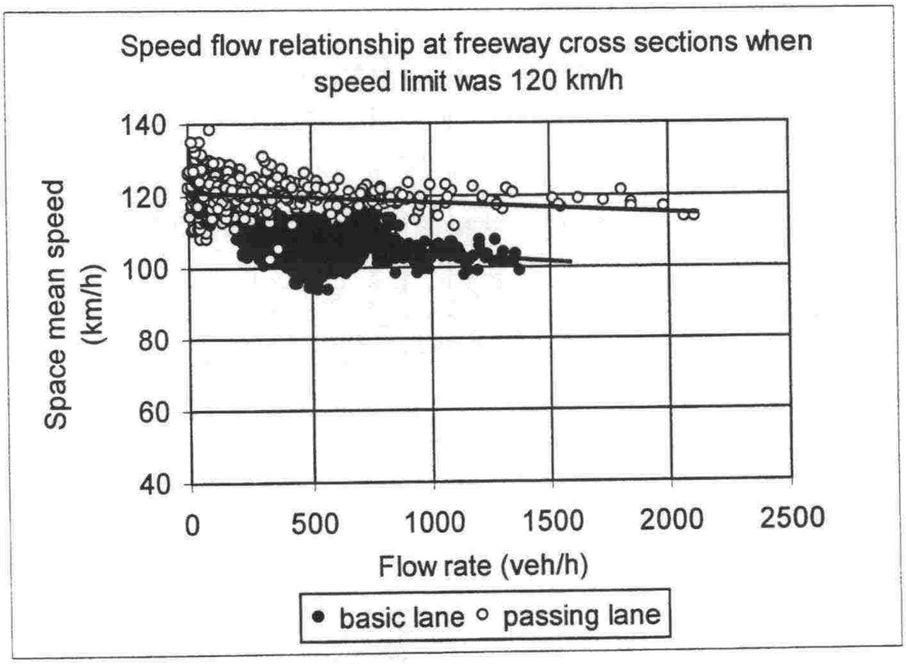

Figure L-3. Speed flow relationship at freeway cross sections when speed limit was 120 km/h.

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